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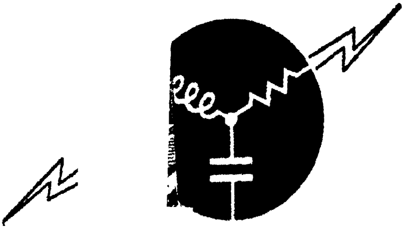
PRINCIPLES
OF
ELECTRICITY
ILLUSTRATED

A PRACTIC L GUIDE FOR BEGINNERS
AND MORE EXPERIENCED CRAFTSMEN
ENGAGED IN ELECTRICAL WORK

Edited by
C. NORRIS
Technical Editor, "Electrical Trading and Radio Marketing"



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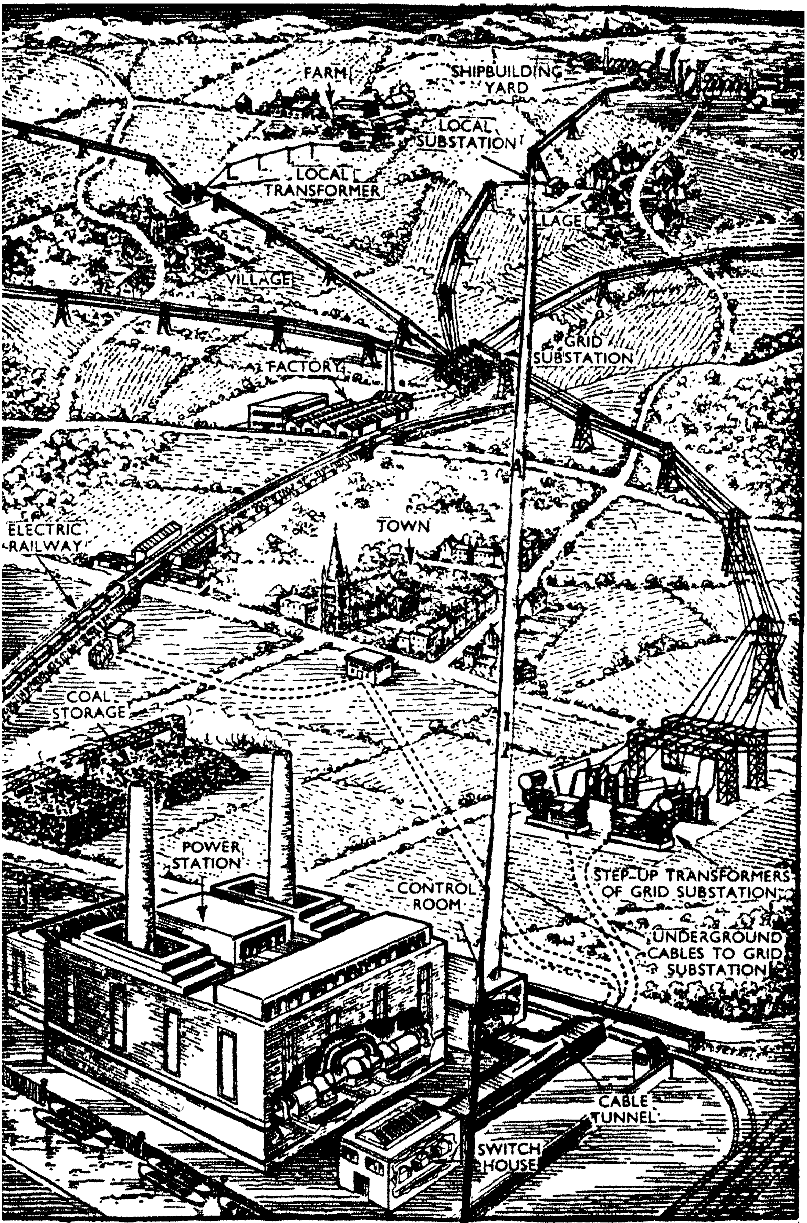

DISTRIBUTION OF ELECTRICITY BY THE GRID SYSTEM

By means of the British Grid System, electrical power is transmitted at high voltages with very low loss over comparatively long distances. Local substations and transormers reduce the pressure to voltages suitable for the various types of consumer.

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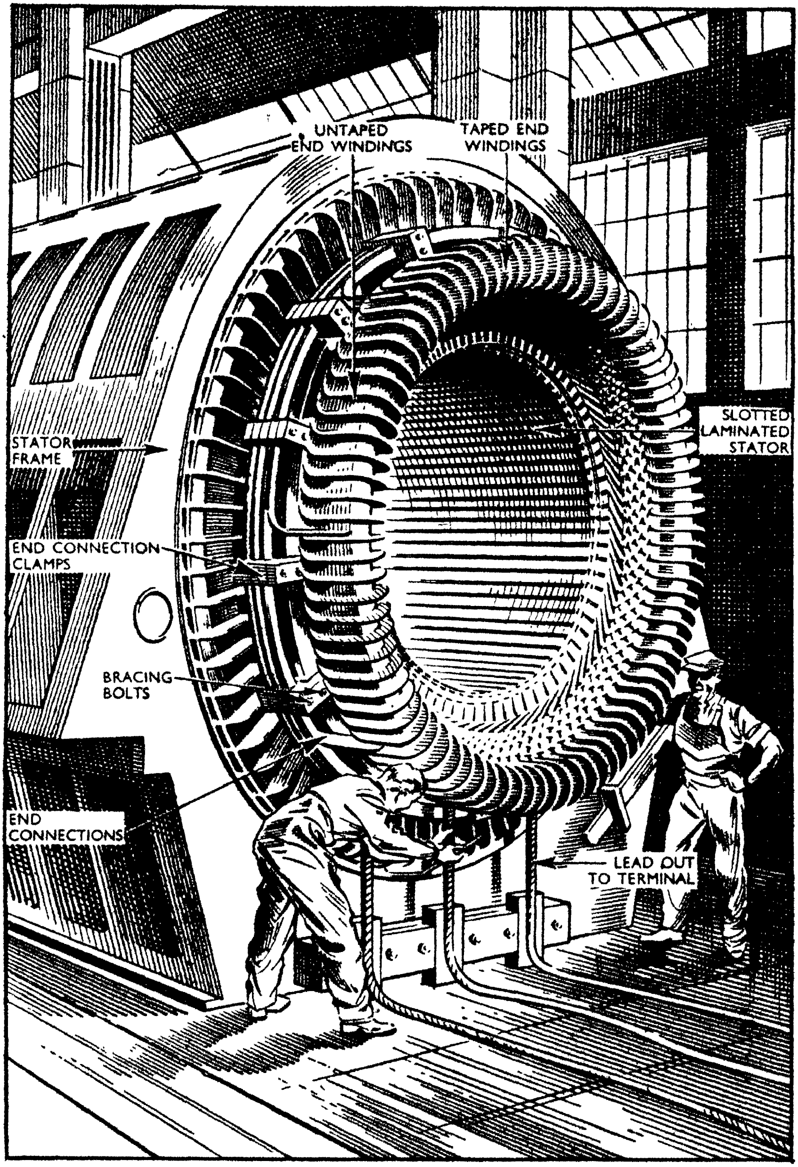


STATOR FOR AN ELEVEN-THOUSAND-VOLT GENERATOR

Final stages in the assembly of the stator of a G.E.C. three-phase generator which will develop 50,000 kW at 11,000 volts. This giant machine is designed for coupling to a steam turbine, which will drive it at a speed of 1500 r.p.m. The rotor, which is not shown here, carries the field windings, and the exciter that supplies them with direct current is itself a large machine, having a full-load rating of 176 kW and, in its turn, requiring D.C. from an auxiliary exciter.

CHAPTER 1

PRIMARY AND SECONDARY BATTERIES

ATOMS AND ELECTRONS. SOME SIMPLE EXPERIMENTS. ELECTRICAL CHARGES. POSITIVE AND NEGATIVE. PRIMARY CELL. CURRENT AND PRESSURE. POLARIZATION. E.M.F. OF A CELL. ELECTRODES AND ELECTROLYTE. LECLANCHÉ CELL. "DRY" BATTERIES. INTERNAL RESISTANCE. PARALLEL AND SERIES. SECONDARY CELLS. CHEMICAL ACTION. CHARGE AND DISCHARGE. USE OF ACID TESTER.

So extensively are electrical devices employed, that a very large number of people need a sound knowledge of electricity. First, there are all those whose work is affected in some way by electrical apparatus; secondly, there are all those who are directly employed in the electrical industry, and their number is great.

It is the purpose of this book to provide an explanation of how electrical power is generated, distributed and put to use (Fig. 1), an explanation in simple language illustrated with practical diagrams.

What Electricity Is

Many people are deterred from a study of electricity by an idea that it is something invisible, elusive, dangerous, and correspondingly difficult to grapple with mentally. The fact is, however, that electric current consists of little particles, or units which correspond to particles, which behave very much like little balls being pushed through a tube.

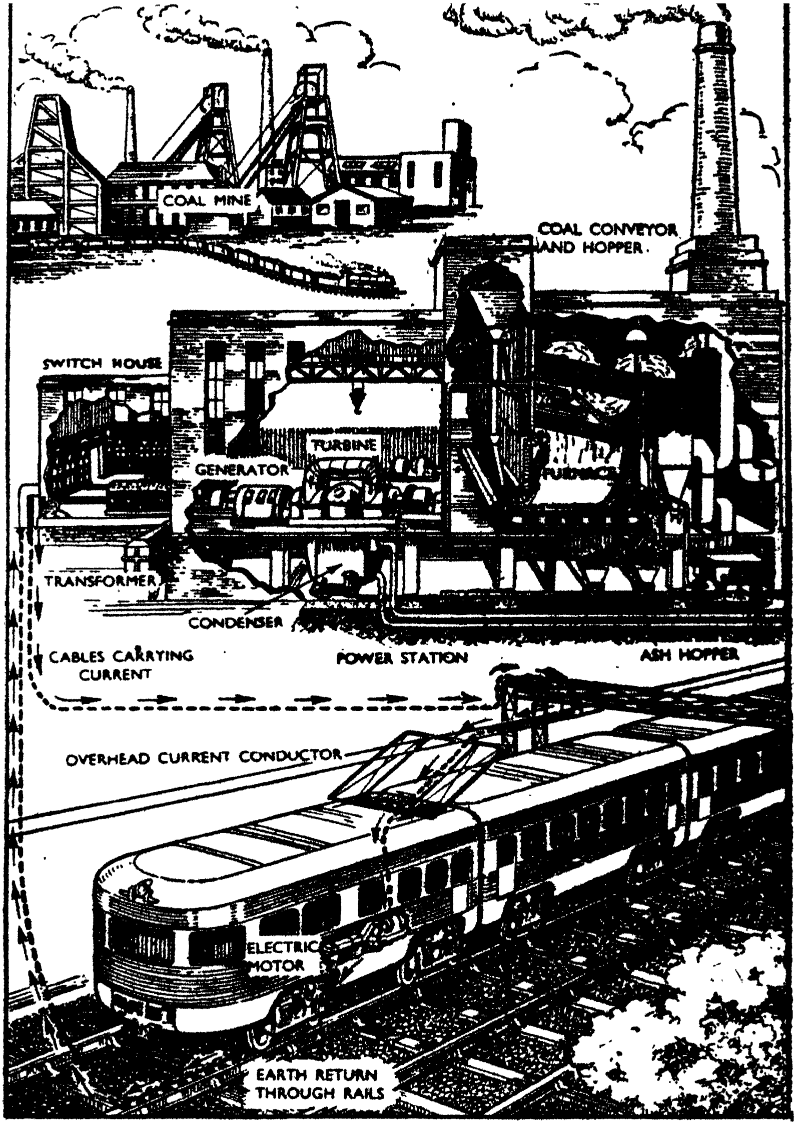
Once we visualize these little particles—we can invent our own personal mental picture of them—electricity becomes something tangible and almost mechanical. In fact, electricity is a form of matter, and electric current is matter in motion; in other words, a means by which energy is conveyed from one point, or state, to another.

Now what, more exactly, is this electric particle to which we refer?

If we were able to go on cutting up a piece of lead into smaller and smaller pieces, eventually we should come to an extremely minute particle which could not be further divided. That small particle is, in the chemical sense, the smallest unit of lead that we can get. It is called the atom.

Of recent years this atom, previously thought indivisible, has been broken up into still smaller things.

Fig. 2a shows, diagrammatically, what the atom of hydrogen is supposed to be like. It is the simplest atom known and has only two parts. There is a central nucleus in which nearly all the weight of the atom is concentrated. Around this nucleus there moves in an orbit a minute particle, the smallest unit of electricity, called the *electron*. The dotted line in Fig. 2a is there only to suggest its path. Each atom of every element has



GENERATION AND UTILIZATION OF ELECTRICITY

Fig. 1. Simplified representation of the generation and use of electricity. Source of power is the latent energy of coal. This energy is released in the form of heat when coal is burned, and is converted into pressure of steam in the boilers. Mechanical power is developed in the turbine and then transformed into electrical power by the generator, so that it can be redeveloped where it is required.

a nucleus and a number of electrons moving round it (hydrogen is the only atom with but one electron). Each electron moves in its own orbit, that is to say, it follows a definite course round the nucleus like the earth does round the sun.

All the orbits are not necessarily of the same size. In an atom with many electrons, there is a pair in orbits near the nucleus; then, farther away, eight in orbits which are all of the same size; then, eighteen, all eighteen orbits the same size, still farther away, and so on.

Let us consider a practical example. That black material, carbon, is known to all of us. If it happens to have been made by burning wood we call it charcoal.

The structure of the carbon atom is shown in Fig. 2b. The dotted lines indicate the four outer orbits, each with one electron, and the thin continuous lines show the two inner orbits, each with one electron. The complexity of the diagram for only six electrons is bad enough, and we can imagine what it would be like for lead, which has eighty-two electrons. That is why the hydrogen atom, with only one electron, is the example most frequently illustrated in articles and books.

A difficulty is now encountered. The student, politely agreeing that a piece of, say, copper is composed of atoms of the kind we have discussed, at once comprehends that there is a great amount of empty space. So, he ponders, why do we see the piece of copper as a solid?

The answer is appreciated when we realize that our eyes, though marvellous, are limited in their ability to see small things. We see only a general mass effect. Perhaps a comparison will help us. When we examine a newspaper photograph with a magnifying glass, we can detect that the picture is made up of thousands of dots. Yet the general effect without the glass is of a picture of gently graded tones of grey. This is because the dots are so close together that we do not at once see them separately.

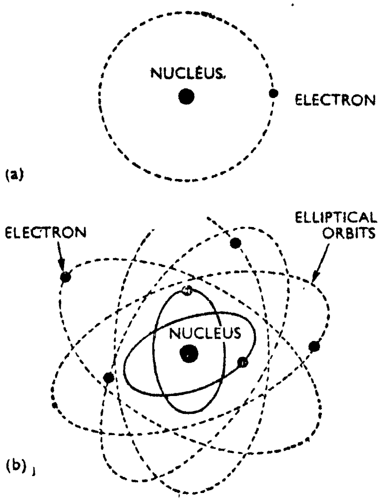


Fig. 2. There is one electron in the hydrogen atom (a); structures of other atoms, such as carbon (b), are complex.

Very Small Measurements

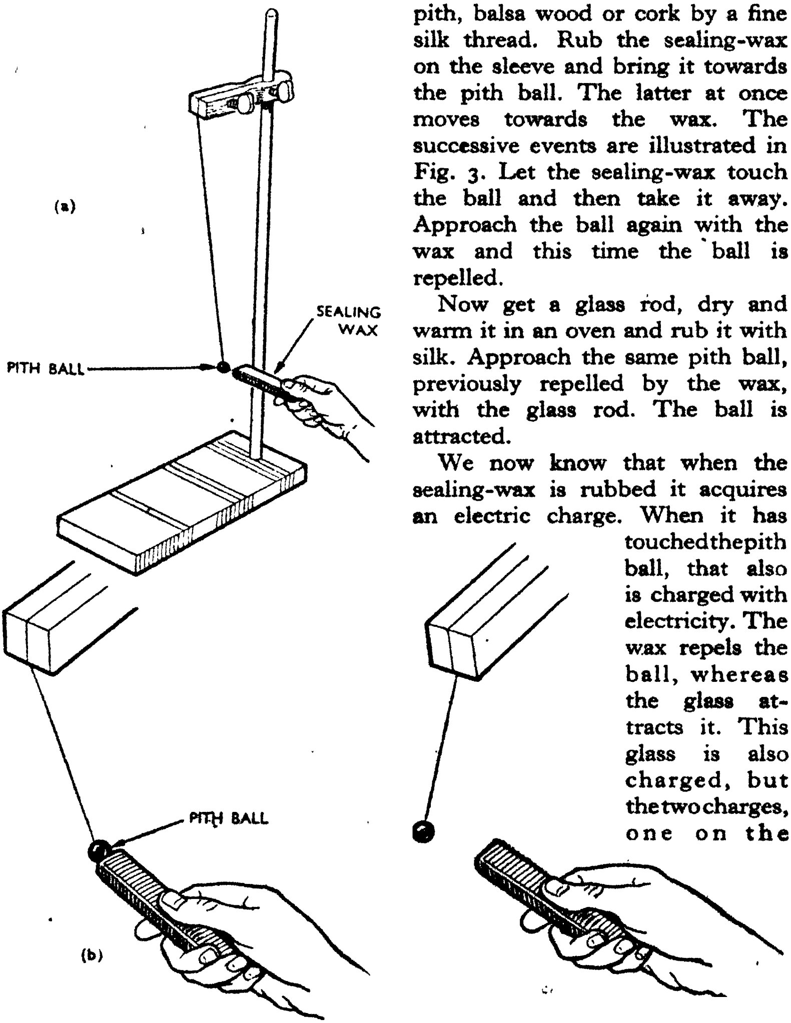
Similarly, we cannot see the separate spaces between the electrons and nuclei of a lump of copper. In fact, no method of magnification has yet been invented to show these spaces. The radius of a hydrogen atom is taken to be about one hundred-millionth of a centimetre, which is about one fifty-thousandth of the limit to which a gauge-maker works.

What has all this to do with electricity? Before answering that question let us for a moment consider a simple experiment which any one can carry out. If we take a stick of ordinary sealing-wax and rub it vigorously on a tweed sleeve, we can get very interesting effects with it. A small piece of paper will stand on edge on the table when the wax is brought near and then leap up and stick to the wax. Materials other than wax, fountain-pen vulcanite, for example, will serve, but not so strikingly.

Now suspend a small pill of pith, balsa wood or cork by a fine silk thread. Rub the sealing-wax on the sleeve and bring it towards the pith ball. The latter at once moves towards the wax. The successive events are illustrated in Fig. 3. Let the sealing-wax touch the ball and then take it away. Approach the ball again with the wax and this time the ball is repelled.

Now get a glass rod, dry and warm it in an oven and rub it with silk. Approach the same pith ball, previously repelled by the wax, with the glass rod. The ball is attracted.

We now know that when the sealing-wax is rubbed it acquires an electric charge. When it has touched the pith ball, that also is charged with electricity. The wax repels the ball, whereas the glass attracts it. This glass is also charged, but the two charges, one on the



PROVING THE EXISTENCE OF AN ELECTRIC CHARGE

Fig. 3. Simple experiment proving that a stick of sealing-wax acquires an electrical charge when vigorously rubbed on wool. (a) Charged wax attracts the suspended pith ball; (b) they touch; (c) on making a second approach, the ball is repelled.

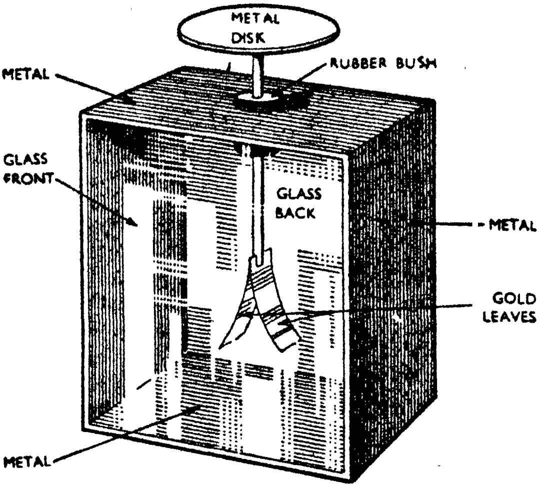


Fig. 4. More scientific demonstration with the electroscope of presence of electric charges. Like charges repel each other and the gold leaves open outward.

wax and the other on the glass, are *in some way different*.

There are thus seen to exist two kinds of electric charge. Many years ago the words *positive* and *negative* were given to them and the terms are still used.

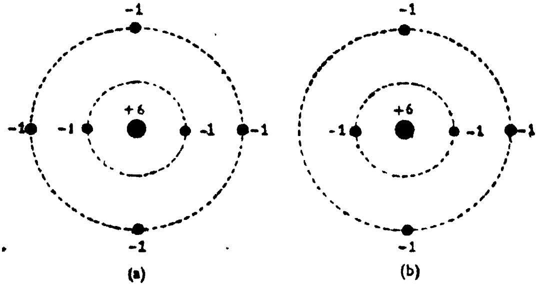


Fig. 5. Normally, a carbon atom possesses six electrons (a). Upsetting the balance by removing one electron (b) would give the atom a positive charge.

Concerning Atoms

We can now forget our little experiment and go back to our consideration of atoms. It should be mentioned, however, that if any difficulty is found in getting repulsion between wax and ball (and the humidity of the atmosphere affects the experiment very much), then two balls should be suspended so that they touch. If the wax is brought slowly up underneath them, they move away from each other. A more scientific instrument for showing the same phenomenon is illustrated in Fig. 4.

We have already said that an atom has a nucleus surrounded by electrons. Soon after the electron theory was discovered we found that, using the words previously in vogue, the electron carries a *negative* charge. The next step was to show that the nucleus carried a *positive* charge. In a normal atom the positive charge on the nucleus exactly equals the total negative charges on all the electrons surrounding that nucleus.

Using the conventional signs, — and + for negative and positive, the carbon atom is now shown as in Fig. 5a. For simplicity, we no longer try to show the two inner electrons in separate orbits, and the four outer electrons in separate orbits. We note that the nucleus has a charge of +6 units and that the total electron charge is −6 units. Thus, the charges are balanced.

Each atom of the same material has the same number of positive and negative charges, but an atom characteristic of one element has a different number of charges from an atom characteristic of another element. For instance, copper has a nucleus of +29 units, and a total of 29 electrons making −29 units.

The word "normal" has been used above, for every atom which has its positive and negative charges equal is neutral and has no charge as a whole. To get electric charges detectable we interfere with atoms and upset the balance.

Effect of Friction

When a piece of sealing-wax is rubbed, heat is generated by friction and this detaches some outer electrons from the atoms of the rubbing material and forces them into the atoms of the sealing-wax. This has, therefore, an excess of electrons, and so, on balance, is negatively charged.

On the other hand, a deficiency of electrons, which, of course, is equivalent to an excess of positive units, called *protons*, makes a positive charge. In Fig. 5b is shown a purely hypothetical diagram of a carbon atom with only five orbital electrons, which is, therefore, positively charged, for, normally, a carbon atom possesses six electrons.

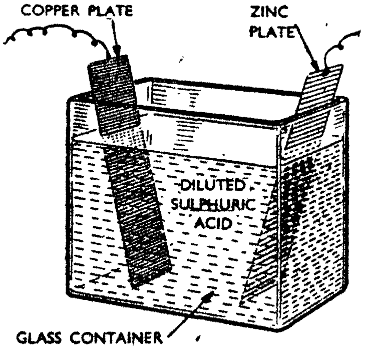


Fig. 6. Simple cell consisting of two plates, one copper and the other zinc, immersed in diluted sulphuric acid.

The electron is today considered to be the smallest possible quantity of electricity; we cannot have half an electron. The charge is very small, so small that ten billion of them passing through a metal wire every second make a current, as it is called, of only about one and a half microamperes. We shall soon meet the word "ampere" as the unit of current, together with its smaller associated units, milliampere and microampere. The electron unit is so small that we rarely need to measure a current in terms of electrons per second.

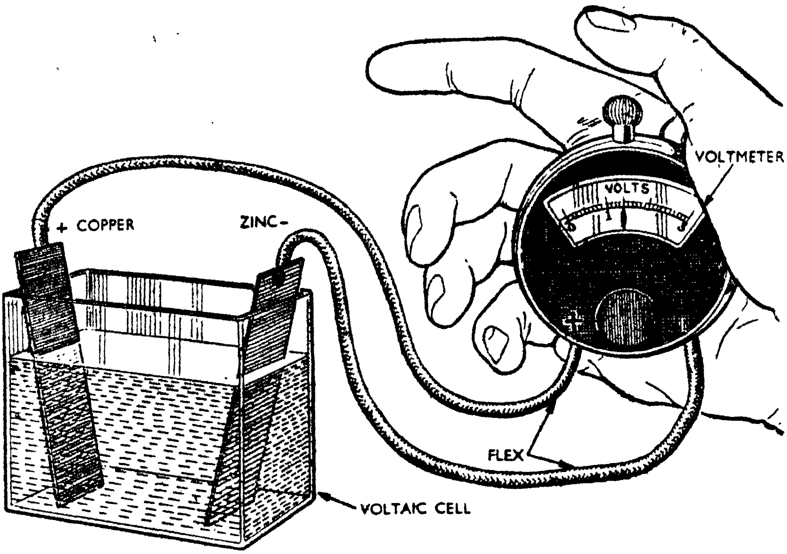
Simple Cell

The student will wonder if there is any means of causing excesses or deficiencies of electrons other than the crude methods, useful only for simple tricks, already shown. We shall see that there are other methods, and we may consider one of them at once.

The elementary theory of the simple cell is the basis of all batteries: so we can profitably consider it in some detail. It is shown in Fig. 6.

The positive pole is a sheet of copper and the negative pole is a sheet of zinc. The liquid, *electrolyte* as we call it, is diluted sulphuric acid. The container is made of any material which is not metallic and on which the acid has no chemical action.

How can we tell that this cell is creating electricity? We no longer



MEASURING ELECTRICAL PRESSURE

Fig. 7. By means of a voltmeter, electrical pressure can be determined.

trifle with pith balls. We can connect across the two poles an instrument called a *voltmeter*, which measures the *electromotive force* (e.m.f.). This is the name given to the force which drives the current and it is measured in *volts*, or in larger or smaller units called kilovolts (1 kilovolt = 1000 volts), millivolts (1 millivolt = one-thousandth of a volt), or microvolts (1 microvolt = one-millionth of a volt).

In Fig. 7 a voltmeter, reading up to 3 V, is shown connected to a simple cell (*voltaic* cell, to give it its correct name). Ordinary flex, bared at the ends, as used for pendant electric lamps, is employed to make the connections. The copper must be connected to the positive terminal on the voltmeter or we get no reading. We see from the diagram that the e.m.f. of the voltaic cell is just over 1 V. The construction of a voltmeter will be considered in a later chapter. For measuring the *current*, we must use an instrument known as an *ammeter*.

Current, as already hinted, is the rate at which electrons are being driven from one place to another, and is a different thing from the e.m.f., which is the driving force. In fact, electric current and e.m.f. can be compared to water current and water pressure, the latter being necessary to create the former, and we often use the expression *electrical pressure* instead of e.m.f.

Measurement of Current

Now let us examine the current obtained from a voltaic cell. In the ordinary way, a battery would be discharged through a lamp or resistance and this would limit the current to a value well within the capabilities of the cell. A current-measuring meter, or ammeter, would be connected between the lamp or resistance and the battery. For this experiment, however, we will break the rules and join the ammeter directly across the cell as in Fig. 8. As the meter has very low resistance it will take a heavy current. We watch the needle.

First, it is at about 1·4 A (the exact value depends on the size of the cell). As we watch, however, we notice an interesting fact, the reading gets smaller and smaller until, at last, there is no reading at all. Therefore, with this cell we cannot drive a constant current, and this fact is a disadvantage. The cause of this fall in current is what is known as *polarization*.

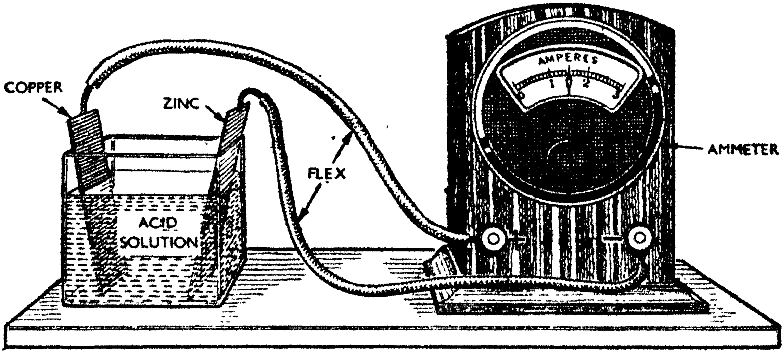
"Making" Electricity

If we could get rid of this polarization we should have a convenient device for manufacturing electricity. This can be achieved, but before we describe the means of doing it, we must look for a moment at the cause of the cell's behaviour.

The first thing to understand, surprisingly enough, is what happens when a substance dissolves in water. Fig. 9 shows some salt being dissolved in water. In (a) the salt is on a fold of paper. In (b) the salt is in the water, which is being stirred. In (c) the salt has dissolved. What has happened to it? Where has it gone?

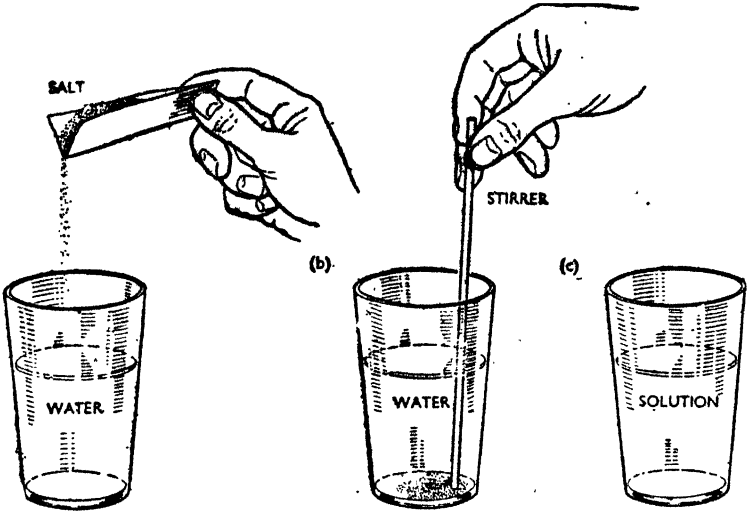
Before we can answer this deceptively simple question, we must go back to our atoms. We have said that every element can be divided into atoms. But there are only ninety-two known elements in the universe; what are all the thousands of different substances, solid, liquid and gas, around us?

The answer is, they are either mixtures or compounds of the elements. And if we divide a compound into its smallest parts, these are not atoms but *molecules*. For example, common salt consists of the elements sodium and chlorine. These are combined in such proportions that one molecule of salt consists of an atom of sodium and an atom of chlorine, firmly tied together by the electrical forces of nuclei and electrons. Another example is that the red pigment of our blood consists of a compound of the elements carbon, hydrogen,



CURRENT-MEASURING METER

Fig. 8. Ammeter connected to copper and zinc plates of simple cell to measure current output. But, as stated in text, ammeters are not normally so connected.



COMPOSITION OF A TRUE SOLUTION

Fig. 9. Salt is put into water (a); stirred (b); and the result is clear solution (c).

nitrogen, sulphur, iron and oxygen.

When a substance dissolves in water, its molecules split up. Each part attaches itself to some water molecules and the groups move about, pressing on each other. So the solution, consisting of separated groups of molecular size, is transparent. (Many fluids are suspensions, like muddy water, or emulsions, like milk. We are concerned only with true solutions, which are transparent, even when coloured, if sufficiently thin layers are taken.) This is what happened to the salt illustrated in Fig. 9.

When the molecule splits, each part may have just the right number of electrons to balance the nuclei. But it may not, in which case the groups are electrically charged and are known as *ions*. An example of the latter kind of solution is that of salt; the sodium atoms are deprived of electrons and are, therefore, positive ions, and the chlorine atoms are negative ions.

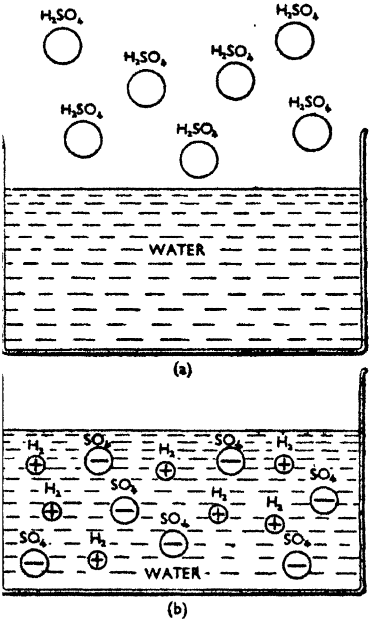
Sulphuric acid is a compound of hydrogen, sulphur and oxygen. When it dissolves in water, each molecule *dissociates*, as we say, into positively-charged hydrogen ions and negatively-charged ions of sulphur and oxygen combined.

Chemical Action

Fig. 10 illustrates the principle of the dissolving of sulphuric acid in water. Molecules of acid, chemical formula H_2SO_4, are shown above the water and then actually dissolved in the water. Of course, accurate relative sizes and shapes cannot be given; the drawing merely illustrates the principle pictorially and is not intended to be taken as an accurate picture.

Now, if we put a piece of copper in the sulphuric acid solution, an electric tension, or force, is at once established between the copper and the solution. Earlier in this chapter we saw that each element had a certain number of electrons and that these were arranged in "shells," two to the inner one, eight to the next, and so on.

The copper atom has its inner shell complete, the next complete, and the next again complete, and then, in the fourth shell, has only one electron, whereas the full complement is thirty-two. We can readily understand that the easiest change, therefore, for a copper atom is to lose this one outer electron. In the solution are hydrogen ions each lacking just one electron. Hence, there is electrical attraction. The e.m.f. set up is just over half a volt.



(a)

(b)

Fig. 10. When sulphuric acid is dissolved in water, its molecules (a) are dissociated into positively-charged hydrogen ions and negatively-charged ions of sulphur and oxygen (b).

When a piece of zinc is also put into the acid solution, again an e.m.f. is set up, measuring also just over half a volt. The combined e.m.f. of the cell thus made is, therefore, just over a volt.

The e.m.f. of a cell exists at the contacts of the *electrodes*, as we call them, or poles, with the liquid, known as the *electrolyte*. If we increase the size of electrodes, the e.m.f. remains unaltered, because it depends on the tension between the electrode material and the electrolyte. We can get a different e.m.f. only if we use different electrodes or electrolyte.

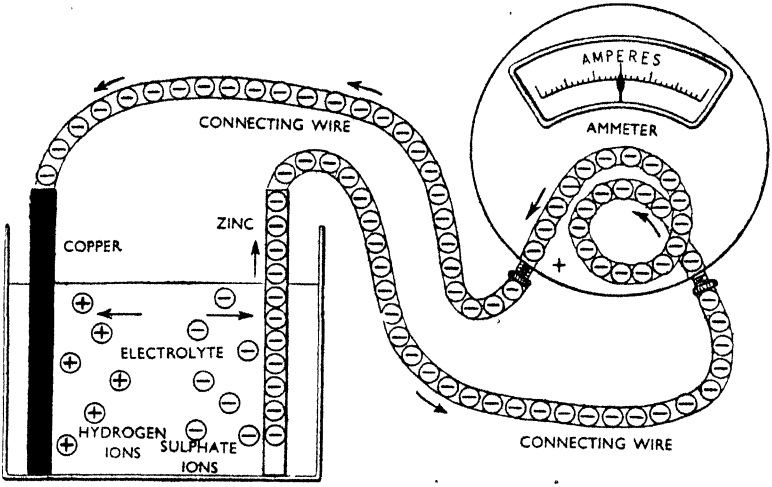
Completing a Circuit

Now let us see what happens when the copper is joined to the zinc by means of a copper wire and an ammeter. This is illustrated diagrammatically in Fig. 11.

The extra electrons on the SO_4 ions (the "sulphate" ions) are released to the zinc. The neutralized ions combine with the zinc to form zinc sulphate, which dissolves in the water. Thus, the zinc is gradually eaten away and the sulphuric acid is used up. The electrons now have a path through the ammeter and connecting wire to the copper plate.

Meanwhile, the positive hydrogen ions have torn away the electrons they need from the copper atoms, which are thus positively charged. The neutral hydrogen molecules form bubbles and some of them rise to the top of the liquid. The electrons, travelling through the conductor from the zinc, supply copper atom deficiencies and so the whole balance is restored.

Ions move through the electrolyte all the time, and more sulphate ions approach the zinc while more hydrogen ions approach the copper. Thus, there is a continuous movement of electrons in the ammeter



FLOW OF ELECTRONS

Fig. 11. Schematic diagram of the passage of electrons from the zinc plate of a cell through an ammeter and connecting wires to the copper plate.

and conducting wire. This continuous transfer is electric current and is measured, as previously stated, in amperes, or multiples or submultiples of an ampere.

The direction of the electron motion is opposite to what is always conventionally accepted as the direction of the current.

This is a point which is always very confusing to the student. In the early days of our knowledge of electricity, it was assumed that an electrical current flowed through a circuit from positive to negative. And, in practical work, this convention is still followed. But the electron theory disproves it, for a flow of electrons is a current of electricity and, as we have seen, electrons always move from negative to positive.

No doubt, in due course, the old convention that current flows from positive to negative will be entirely discarded, but until it is students will continue to encounter this little point of perplexity. Many of the hydrogen molecules, however, when neutralized, stick to the copper plate and decrease the area of copper in contact with the electrolyte. This tends to reduce the current. At the same time, the approaching hydrogen ions, not being able to get to the copper, and being positively charged, set up a sort of "back e.m.f." in the liquid. The combination of both effects makes the current decrease and is the cause of the polarization to which we have referred.

The cure for polarization is the addition to the cell of some device which will stop the accumulation of hydrogen on the copper plate, or, in general, on any positive plate of any cell whatever. With such a device added, we have a cell which will give a continuous current for some time, a cell of great practical value.

We have dealt with the voltaic cell in some detail so that we can

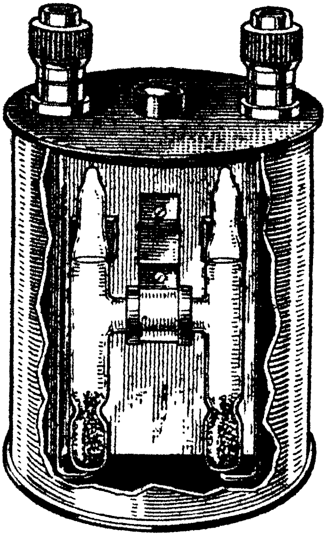


Fig. 12. Weston cadmium standard cells are used only in research laboratories.

gain a clear understanding of the electronic basis of its action. We need not treat other cells in such detail. Instead, we can lump together the various effects which occur under the term "chemical action."

Many people have devised primary cells utilizing different electrodes and electrolytes and antipolarization devices, all with the purpose of gaining greater efficiency and greater e.m.f. There have been the Daniell cell, the Poggendorf cell, the Bunsen cell, and so on. Today, the only one widely employed is the Leclanché cell, though there are standard cells, such as the Weston (Fig. 12), in use in research laboratories.

The Leclanché cell is illustrated in Fig. 13. The positive electrode is a bar of hard carbon. The negative electrode is a zinc rod and the electrolyte a solution of ammonium chloride (sal-ammoniac) in water. The depolarizer is manganese dioxide, a black substance with a great affinity for hydrogen. This is in granulated form and must be held round the carbon plate by means of something rigid. At the same time, this rigid container must allow the electrolyte to reach the carbon. In practice, both necessities are met by using a pot made of porous porcelain.

Leclanché Cell

The e.m.f. of the Leclanché cell is 1·5 V. The depolarizer is effective but slow, and, therefore, the cell can be used efficiently only for short intervals, with periods of rest between to permit the depolarization to be completed.

The water evaporates in the course of time and the zinc and sal-ammoniac are used up. So periodic inspection and treatment are necessary. The disadvantage of

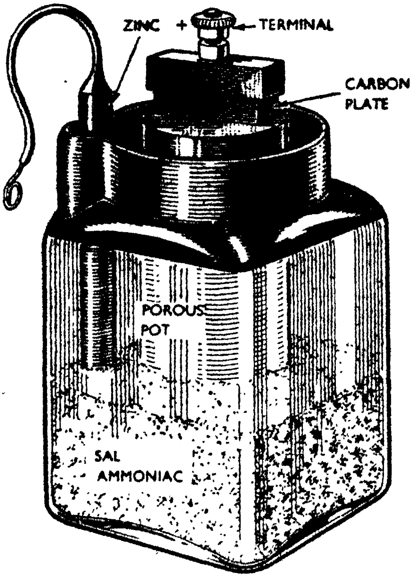
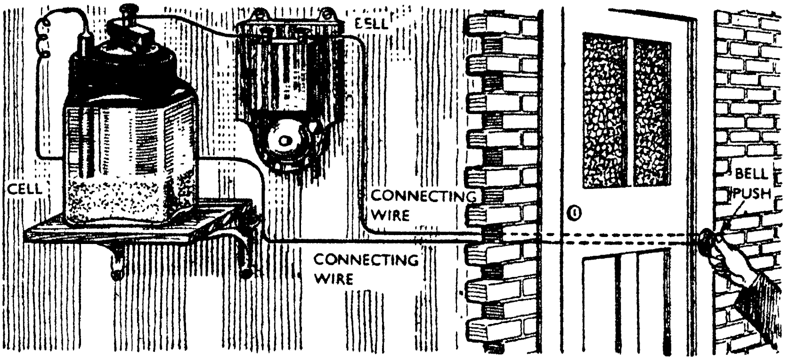


Fig. 13. Effective depolarizer is contained in porous pot of Leclanché cell.

this cell is its messiness, because the white sal-ammoniac creeps over the edge and along the conducting wire and the shelf on which the cell is usually placed.

The "inert" Leclanché is a special form. The outer container is unbreakable and the sal-ammoniac is packed inside quite dry. There is an opening in the pitch composition used to seal the top. This cell is quite inactive until water is poured into the opening, and in its inert state it can be safely transported and does not deteriorate.



SIMPLE ELECTRICAL CIRCUIT

Fig. 14. How the electrical circuit of a simple bell system is completed.

Fig. 14 shows how a Leclanché cell is used to ring an electric bell.

Each cell of the popular "dry" battery used in torches and for radio set batteries is a Leclanché cell as far as the chemical action is concerned. A glass container is not used but the zinc electrode is made in the form of a hollow cylinder or container. The positive pole is a carbon rod on the top of which a brass cap is fitted.

In place of the porous pot, a canvas or linen bag is used, and the electrolyte is in the form of a paste made by adding gelatine or flour. Each manufacturer has his own special methods of construction, and the details given above should be taken as merely the basis. The top of the container is filled with a hard-setting pitch composition through which a small outlet is made to allow the escape of gas. Fig. 15 shows the construction of a dry cell.

Such a cell is portable and can be used in any position. It is rigid enough to withstand a limited amount of rough use, whereas the ordinary Leclanché cell has a breakable glass container and must be kept upright and cannot easily be carried about. Note, too, that the dry cell is not really "dry."

Why Cells Deteriorate

As the cell is used, the zinc is eaten away and the water evaporates. In this way, the cell deteriorates. Even when kept on a shelf, the water evaporates and the cell slowly deteriorates even though it is not used. That is why, in some circumstances, the inert Leclanché is preferable.

After a time, the length depending on the current driven by it,

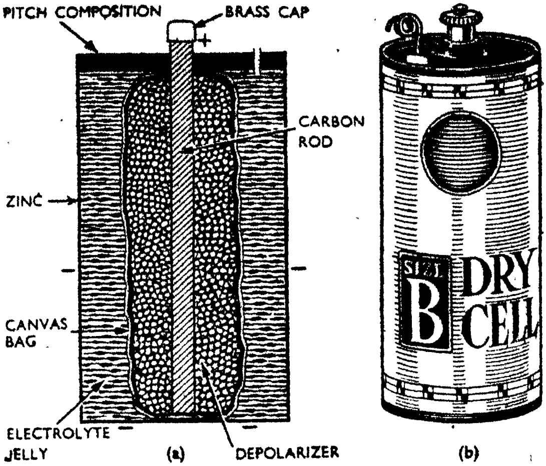


Fig. 15. Construction of a dry cell (a) shown in section; external appearance of one of large size (b).

the cell is of no more use. Sometimes, if the fall of e.m.f. is due to evaporation and the zinc container is still watertight, the addition of water will renew the cell for a short time. Occasionally, heating will drive off gases and expand the jelly electrolyte so that a moist part previously held from the zinc by dried sal-ammoniac will again make contact. Then we have an apparent renewal of the cell. But these renewals are awkward to make and not dependable and, in general, we may say that a dry cell when used up is finished and fit only for salvage.

We can test the cell by means of a voltmeter. The positive terminal of this should be connected to the brass cap and the other terminal to the zinc. The reading should be 1·5 V. This decreases to about 1·2 V during use, stays there some time and then rapidly falls.

In any cell, whether of the types already mentioned or those to be described later, an increase of the size of plates does not affect the voltage (e.m.f.). Nevertheless, we feel that there must be some difference between the behaviour of a cell with small electrodes and one with big electrodes and, of course, in a bigger container holding more electrolyte. What that difference is we can soon learn.

The fact that the e.m.f. is not increased can be appreciated by an analogy. We know that atmospheric pressure is measured in pounds per square inch. So if, for example, we double the area of a plate exposed to the atmosphere, we get double the total pressure on it, but that is spread over double the area and so the pounds per square inch remain the same. It is somewhat similar in a cell.

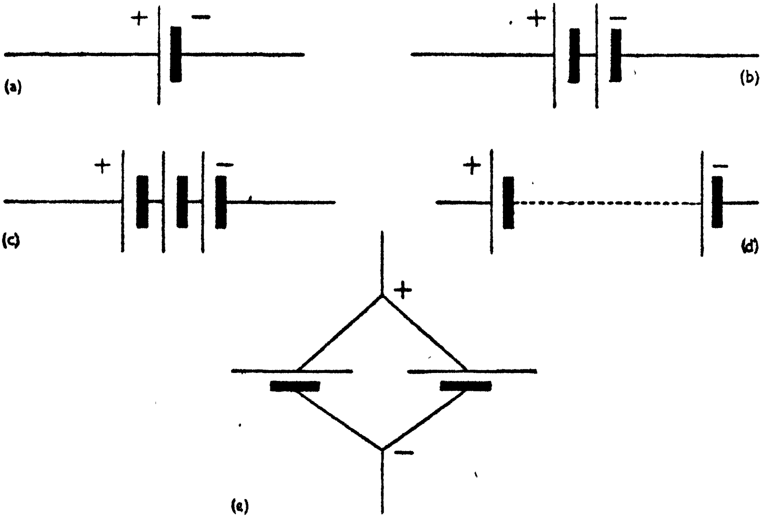
Dry-cell Capacity

There is, however, with a bigger electrode, more of it to be acted upon and so, if it is eaten away when a current is driven, then the bigger the electrode the longer it will last. Therefore, we can say, in general, that the bigger the dry cell the longer it will last, provided we do not try to take a much heavier current from it than from the small cell.

We all know from experience that several sizes of dry battery are on the market. There is the very tiny one used for torches shaped like a fountain pen. There is the very popular No. 8, which consists of two cells, end on end, each about 1⅛ in. long and ¾ in. in diameter. There is the twin-cell battery for cycle lamps, each cell being about 3 in. long and 1¼ in. in diameter, and we know how well this type of battery lasts.

Internal Resistance

But there is more in the size of a cell than just this. We know that the e.m.f. is at the contacts of electrolyte with electrodes. What about the electrolyte in between? This brings us to the matter of *resistance*, which is the opposition in any material to the passage of current.



DIAGRAMMATIC SYMBOLS FOR CELLS AND BATTERIES

Fig. 16. (a) Single cell, with connecting wires; (b) two cells connected in series; (c) three cells connected in series; (d) how a large battery is indicated when it would not be practicable to show all the cells; (e) two cells connected in parallel.

Other things being equal, the longer an electric path is, the greater is this resistance, and the narrower the path, the greater the resistance. Therefore, when we increase the size of electrodes, in effect we make the path wider, and the *internal resistance* is made smaller. We get the same result by securing a shorter path through the electrolyte.

The effect of making the internal resistance smaller is that we can take a bigger current from the cell. An increase in the size of a cell enables us to get a longer life, if the current taken is not too big, and it enables us to take a larger current if we wish. For this reason there are dry cells on the market as long as 8 in. and as wide as 3¼ in. Such cells are more convenient for many purposes than the wet Leclanché cells.

Definition of a Battery

A *battery* is an arrangement of individual cells. The most usual way to join them is *in series*. This means that they are connected end on end, so to speak, and the negative pole of one cell is joined to the positive pole of the next, and so on, thus leaving one positive pole free at one end and one negative pole free at the other, both these being for ultimate connections.

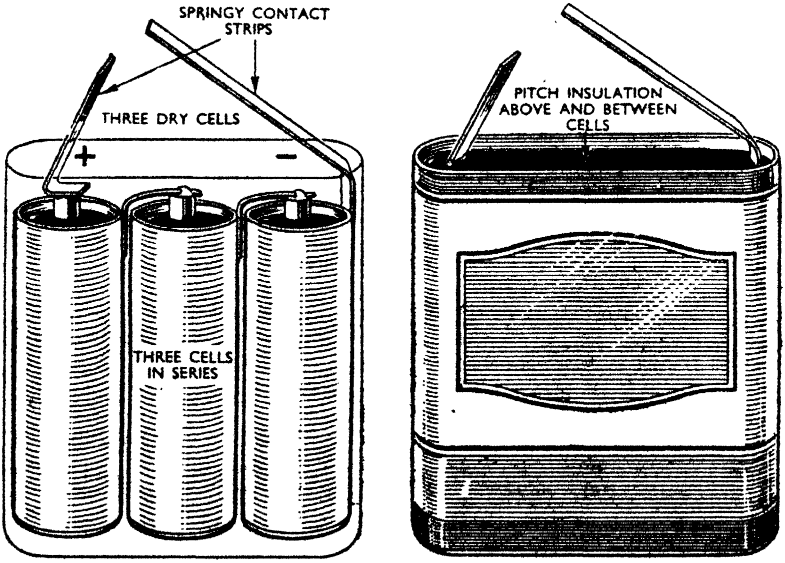
Parallel Connection

Sometimes, for special purposes, we connect cells *in parallel.* When we do this we join all the positive poles together and all the negative poles together. When we draw electrical diagrams, it is not customary to show detailed pictures of all the components but, instead, we use certain conventions, a sort of shorthand. Those for batteries are shown in Fig. 16. The arrangement of a common torch battery is shown in Fig. 17.

There is a difference between batteries consisting of cells in series and those made of cells in parallel. The series case is the commoner. The great advantage of the series method is that we can get a higher e.m.f. For example, two dry cells in series will give us 3 V. Forty such cells in series will give us 60 V. In order to get the total voltage we have merely to multiply the e.m.f. of one cell by the number connected in series.

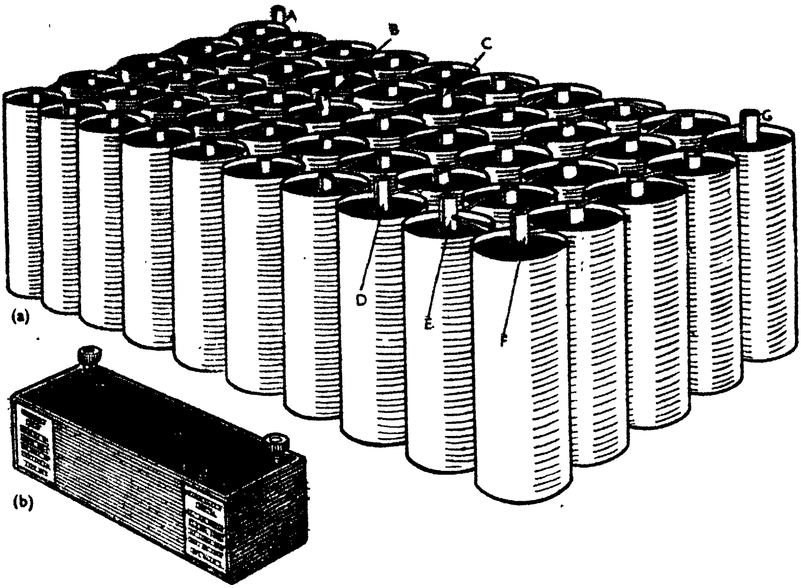
The No. 8 torch battery consists of two dry cells in series, and this is effected by letting the positive pole of the bottom cell touch the bottom of the zinc casing of the upper cell. Then the zinc of the lower cell and the carbon of the upper one are the free poles. In a torch, the free zinc pole is connected to the lamp by means of the outer metal case and the side switch, while the positive pole of the upper cell makes contact with the soldered contact on the end of the bulb.

In larger batteries, we make the connections by soldering a wire from the zinc of one cell to the



CONSTRUCTION OF A TORCH BATTERY

Fig. 17. Cells in a torch battery are connected in series to give required voltage.



H.T. BATTERY FOR RADIO USE

Fig. 18. (a) Showing the arrangement of the cells in a high-tension dry battery. (b) The connecting sockets are marked *A*, *B*, *C*, *D*, *E*, *F*, *G*, and project through the composition. *A* is the negative, and *G* the highest value positive socket.

metal cap of the carbon of the next one, and so on. The large battery used in radio sets, the one called the high-tension battery, is made in this way, as shown in Fig. 18. There is a smaller one called a grid-bias battery, also used in radio sets, usually of 9 V, made of six dry cells in series.

There is one point about the battery of cells in series that we must note. That is, although we get more volts, we cannot drive a larger current than we could with any one of the cells comprising the battery.

Therefore, some people may wonder why we bother to make batteries. The answer is that sometimes we need high volts and sometimes we need high amperes, and sometimes both. So for high volts, we make batteries of cells in series. For high amperes, we make batteries of cells in parallel, because the effect is just as if we increase the size of one cell.

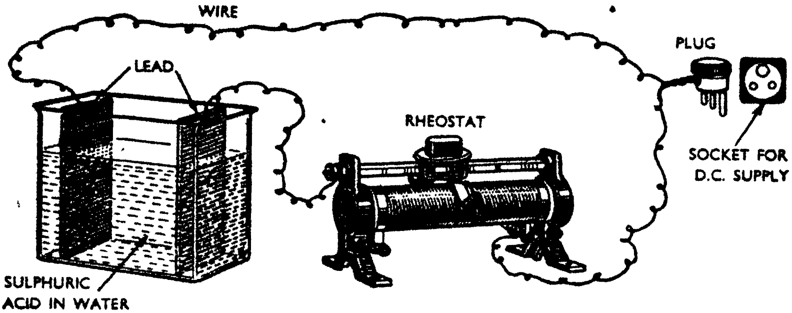
If we need high volts and high amperes, then we must use a battery of large cells in series or else a battery of cells arranged in both series and parallel.

Secondary Cells

All the cells discussed so far are known as *primary* cells because the e.m.f. is the direct effect of the chemical action between electrolyte and electrodes. When that action is exhausted, a cell is useless and must either be scrapped or the electrodes and electrolyte renewed.

There is another sort of cell, in which the e.m.f. is available only a preliminary chemical action has been caused. Such a cell is called a *secondary* cell. In Britain we more usually call it an *accumulator*; in America it is known as a *storage cell.*

The preliminary action can be demonstrated with a D.C. (i.e. direct current, as distinct from alternating current, or A.C.) supply, a rheostat, a glass container, some sulphuric acid, two lead plates and connecting wire. The set-up is shown in Fig. 19. The rheostat slider is adjusted until the chemical action is not too fierce. (It should be noted that actual experiments carried out with mains supplies must be conducted only under the immediate personal supervision of an electrical expert. Mains supplies are lethally dangerous, owing to their comparatively high voltage.)



HOW ACCUMULATORS ARE "CHARGED"

Fig. 19. Passing electric current through the secondary cell causes chemical changes.

Effect on Plates

If we watch the plates we notice that they change. One of them turns brown, while the other, though not changing so noticeably, gets greyer and "velvety" in appearance. Now remove the supply and apply a voltmeter to the lead plates. We find that the brown plate is the positive pole, the other plate the negative pole, and that an e.m.f. is available.

If we use this up and repeat the operations many times, eventually the brown colouring penetrates deeply into the one plate and the other becomes what we call "spongy." This lengthy process is known as "forming" the plates. It is done, or a substitute for it, by the manufacturers before an accumulator is put on the market.

Such a forming process is too long for the commercial world, and a substitute is used when possible. This consists of making the positive plate in the form of a grid and filling the spaces with a paste of, chiefly, an oxide of lead, though the makers do not divulge the exact formula used. The advantage of this device is that the forming is speeded up, because the final condition of the positive plate is really lead peroxide.

The negative plate can also be made in the same way, for, during forming, the oxide is reduced to lead.

We already know that the e.m.f. exists at the contacts of electrolyte and electrodes, so the greater the surface of the latter and the deeper the active material penetrates, the more efficient is the cell. The paste method assists in getting this deep penetration quickly.

Plates made of paste are mechanically weak and, during use, especially if too great a current is taken, they crumble and a sludge collects at the bottom of the container, while the amount of active material on the plates is reduced. Therefore, commercial accumulators must be used carefully, according to the makers' instructions, if we are to get economical length of life from them.

Plate Construction

Negative plates can be made mechanically stronger and yet capable of being formed quickly by constructing them as hollow casings with the active material inside. Such are called "box" negatives. In the textbooks, we sometimes find that the normally formed plates are called "Planté," while the paste plates are called "Fauré," but we generally employ the ordinary terms "paste" and "box" and "solid" according to the construction.

Let us assume that we have a cell with plates already fully formed and the electrolyte is a solution of sulphuric acid in water. Then we have the usual accumulator. The e.m.f. is at first about 2·5 V but, as soon as we begin to use it to drive current, the e.m.f. settles down to 2 V and stays there for a very long time. That is the important point. As long as we do not attempt to take more current than the makers state, we have a constant voltage source of 2 V.

Eventually, the chemical action is completed. Then we appreciate the other great advantage of this secondary cell. For we can repeat the forming process by means of a D.C. supply, connecting the positive cell plate to the positive of the supply, and so *recharge* our accumulator. Then it is available for use once more. A good accumulator can be used for years if it is looked after properly.

Even with a small accumulator of two solid plates, we can drive a bigger current than we can with a dry cell or Leclanché. But we shall see that by careful construction we can make accumulators that will drive very big currents indeed. The brown lead peroxide of the positive plate has excess oxygen and acts as the depolarizer. It is instantaneous in operation, so that the problem which hampers the primary cell is solved.

We have already seen that the electrolyte in a cell offers opposition to the passage of current. The smaller this is, the bigger is the current we can take from the cell without causing its e.m.f. to drop.

Lessening Resistance

The first and obvious way to lessen the internal resistance is to increase the size of plates. There is a limit to this in the case of an accumulator because the cell would become too big to handle.

What we can do is to multiply the number of plates inside one cell and join all the negatives together and all the positives together. This is shown in Fig. 20. The effect is as if we have several cells in parallel. At the same time, the length of electrolyte between electrodes is decreased and we effect a reduction in internal resistance in this way as well.

We can also do something about the actual resistance of the diluted acid. This brings us to the discussion of *relative density*, more commonly known as *specific gravity*, though this expression conveys very little in itself.

The relative density of a substance is the ratio of the weight of a certain volume of that substance to the weight of the same volume of water. For example, if a substance has a relative density of 1·5, then a cubic inch of that substance weighs one and a half times as much as would a cubic inch of water.

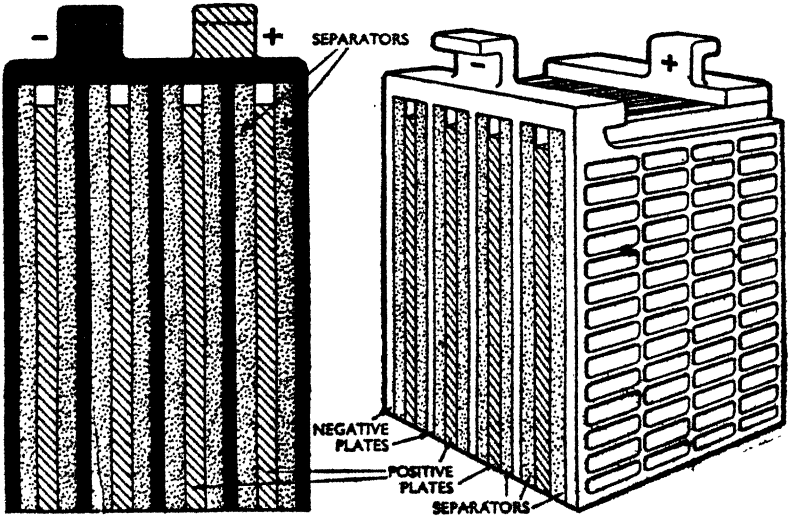
Specific Gravity

Most liquids have relative densities between 0·7 and 2·0. Concentrated sulphuric acid has a relative density (or specific gravity) of about 1·8. It is thus nearly twice as dense as water. If we mix the acid with water, the resulting specific gravity of the solution will be somewhere between 1·0 and 1·8, the exact value depending on how much acid is used in relation to the water. For example, a half and half solution will have a specific gravity of 1·4.

A peculiarity of the solution of the acid in water is that the internal resistance first of all decreases as we add the acid to water and then starts to increase. Therefore, there is one correct proportion at which the resistance is least. This is when the specific gravity is about 1·25.

Incidentally, mixing of acid and water generates heat. If acid is added to a quantity of water, the temperature rises without harmful effect. Careless addition of water to acid, however, makes the acid boil dangerously.

The point of minimum specific gravity is not critical, and any value between about 1·24 and 1·3 is good enough. In small accumulators we usually keep to 1·25, and in accumulators for cars and other vehicles the specific gravity is somewhat higher. So, by making the



REDUCTION OF INTERNAL RESISTANCE

Fig. 20. By using two groups of interleaved plates instead of two single plates, we are able to reduce the internal resistance of the cell.

plates as large as possible, by ensuring that they have large surface areas of active material and that they are deeply penetrated as well, by combining many plates in one cell, with separators between to make sure that the plates do not touch, and by using acid of specific gravity 1·25, we create a source of e.m.f. which will last a long time at a constant value and from which heavy currents can be taken. Without accumulators, many of our activities would cease at once.

Motor-car Battery

The motor-car has a battery of accumulators for operating the self-starter, the lamps, the horn, and the explosion of the gas and petrol vapour mixture which makes the propelling force (Fig. 21).

The container must be of material which is not affected by the acid and is usually glass or celluloid, though in the batteries used in cars the material is one of the stronger plastics.

Most of us are concerned more with using an accumulator than with its charging, so we will consider its use or *discharge* first.

Accumulator Discharge

The process of discharge is sometimes represented by a chemical equation, but as this is somewhat misleading and, in fact, conveys nothing of the atomic, molecular and electronic activities, we shall not consider it here.

As the cell drives current, changes can be observed in the plates. The positive one gets lighter in colour and the negative one darker. The acid is acting upon the lead, and a white substance, lead sulphate, is formed. This is nearly insoluble. It penetrates into the positive plate in the form of crystals and normally is invisible. If we are careless enough to use the accumulator too long, however, we can see the white sulphate.

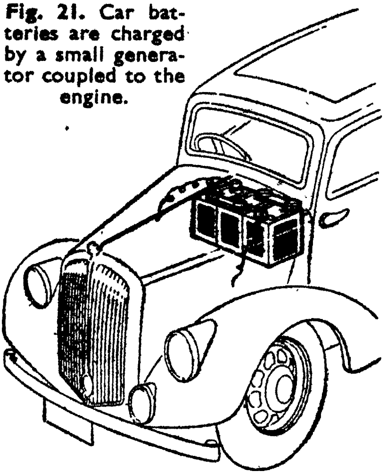


Fig. 21. Car batteries are charged by a small generator coupled to the engine.

Using Up the Acid

At the same time as the visible changes in the plates are taking place, the acid is being used up, but not the water. Therefore, the specific gravity of the solution gets less.

A voltage test is not quite a reliable test of condition, because a voltmeter takes a much smaller current than the apparatus normally connected to an accumulator. A much more reliable test is made by means of an acid tester, which we use to find the specific gravity of the acid.

The acid tester is a glass tube with a rubber bulb at one end and a short length of rubber tubing at the other (Fig. 22). Inside the tube is a small instrument called a *hydrometer*. This is a hollow glass tube, sealed at both ends, with a weight at one of them. The instrument

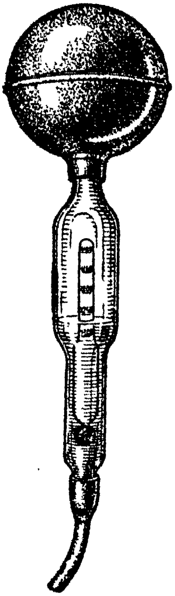


Fig. 22. Acid tester, showing the floating hydrometer inside the tube.

is illustrated in Fig. 23 and it floats upright in any liquid. A scale is marked on the upper part of the tube. To find the specific gravity of any liquid, we float the hydrometer in the liquid and read the scale where it cuts the surface. Thus, the example given in Fig. 23 shows a specific gravity of 1·1.

To use the acid tester, which contains inside it the small hydrometer, we squeeze the bulb, insert the rubber tube in the opening at the top of the accumulator until the tube is below the acid electrolyte and then release the pressure. Liquid is drawn up into the tube and we can hold the tester upright and see through the glass where the scale of the hydrometer cuts the surface of the electrolyte in which it is floating.

At full charge the reading should be 1·25. If the specific gravity is 1·15, the accumulator is fully discharged and must not be used until recharging has taken place. The operation is shown in Fig. 24.

Charge Indicators

Some makers include special devices in their accumulators to indicate the state of discharge. These depend on the specific gravity of the electrolyte. One method is to have three balls of different colours and buoyancy.

A second sinks when the cell is half discharged and the last sinks at full discharge.

Another device is to have the floating ball on the end of a lever, so that it floats at the top in a fully charged cell, half-way down in the half-discharged cell and at the bottom when the cell is discharged. But the normal test is that of the acid tester already described.

Adding Distilled Water

We must take care of the accumulator. The water slowly evaporates, and we must add distilled water occasionally in order to keep the electrolyte above the plate level. We must not allow the discharging

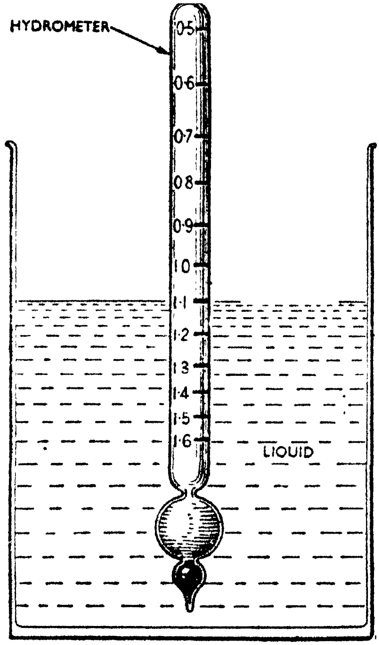


Fig. 23. Relative density or specific gravity of liquid is read on the hydrometer at point where it cuts the surface.

to continue until white sulphate appears, or we shall find that the process of charging is impossible, or, at least, very tricky and difficult. We must not leave the cell in a discharged state, or the insoluble sulphate will harden on the plates and make the cell useless.

Cells Not in Use

If we wish to leave the cell for some time, we should see that it is fully charged and, if we pour out the electrolyte then, we can leave the dried cell for a long time without harm.

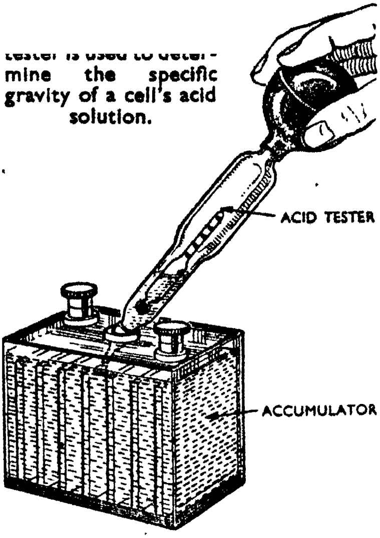
Care must be taken not to "short circuit" the cell. That is, we must not take too heavy a current from it. If we do, the formation of sulphate is so rapid that the cell is damaged.

When the cell is "used up," it has to be recharged. For this the positive terminal, always shown by the use of red and sometimes by the addition of + on the cell top nearby, is joined to the positive end of a D.C. supply, through a rheostat, and the negative terminal of the cell to the negative end of the supply. There should be an ammeter between cell and rheostat or between rheostat and D.C. supply.

After switching on, the rheostat is adjusted until the ammeter shows the correct charging current. This is given on the label stuck on the cell and is decided by the makers. Fig. 25 is a battery charging system.

Charging Rate

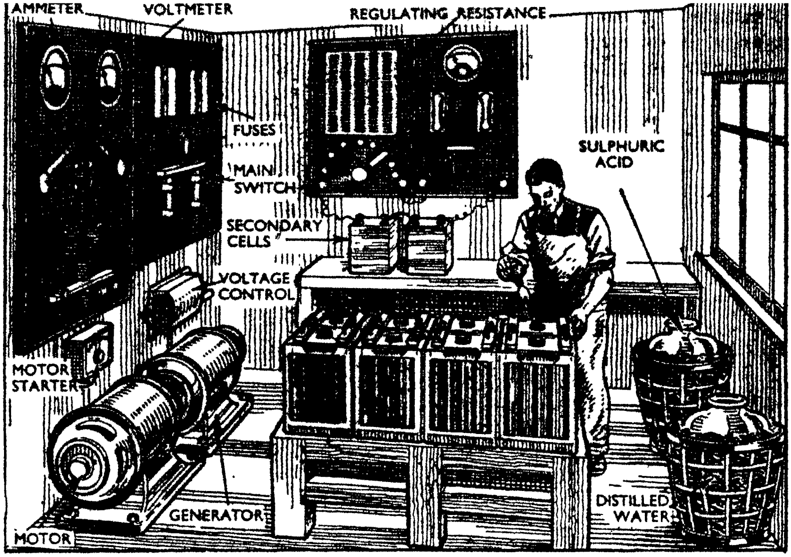
If charging is done too rapidly, by using a current bigger than the correct one, there is a risk of making the positive plates crumble and buckle up. It is safe, however, to charge at a smaller current than the rated one. Practical indications are that the cell is fully charged when it is gassing freely and the acid specific gravity is 1·25.


tester is used to determine the specific gravity of a cell's acid solution.

Accumulator's Capacity

The ability of an accumulator to last and give current is called the *rated output*, or the *capacity*. It is expressed in ampere-hours. Thus, a rated output of 10 ampere-hours means that an ampere can be taken for ten hours, or half an ampere for twenty hours. The rated output is seen to be the result of multiplying current in amperes by the time in hours.

The capacity is decided by the makers, who know just what plate area and active material and other factors of design have been incorporated in the construction. A rough rule for our own use is: Estimate the area of a positive plate in square inches and multiply the figure by the number of such plates. Then, two-thirds of this gives a rated output in ampere-hours. For example, if a cell has



CHARGING STATION FOR HEAVY-DUTY ACCUMULATORS

Fig. 25. Low-voltage direct current is obtained from a generator driven by a motor run from the electricity supply. On the walls are seen resistances for regulating the charging current, meters to indicate current and voltage, fuses, and automatic cut-outs to prevent accumulators discharging back through the generator when it stops. In modern charging shops where only A.C. is available, "static" rectifiers, either valve or metal, are generally employed to convert the A.C. to D.C.

three positive plates each $3\frac{1}{2}$ in. by 2 in., the area of one plate is 7 sq. in. The total positive plate area is, thus, $7 \times 3 = 21$ sq. in. The rated output should be $21 \times \frac{2}{3} = 14$ ampere-hours. The maker's rating may be given as 13 ampere-hours, which is near enough for practical purposes.

Rate of Degeneration

Unfortunately, the degeneration of the plates does not occur in strict proportion to the current. The bigger the current, the faster the plates are used up. So there is one little catch in our calculations of current and time. That catch is—we must estimate a smaller rated output if use big currents.

An example will show what is meant. The cell already mentioned can give a current of 6·6 A for only one hour, which is about half the rated output.

Follow Instructions

We must obey the maker's instructions, and then we are safe. A "short-circuit" current for one cell may be a normal current for another, much bigger, cell. With that note of warning we can leave the matter of cells and batteries and pass on to the next stage of our subject, where we shall be describing the effects and applications of the electrical currents derived from these primary and secondary batteries. This will introduce the reader to some of the vital laws which govern the flow of electricity and how they are developed for use.

CHAPTER 2

ELECTRICITY IN ACTION

CONDUCTORS AND INSULATORS. CONDUCTIVITY IN GASES AND LIQUIDS. ELECTROLYTE. CONNECTORS. ELECTRON FLOW. ELECTRICAL CONTINUITY. SWITCHES. TYPES OF SWITCHES. DIAGRAM SYMBOLS. ELECTRICAL UNITS. MEASURING CURRENTS AND VOLTAGES. RESISTANCE. OHM'S LAW. POTENTIAL DIFFERENCE. HEATING EFFECT OF ELECTRIC CURRENT. BOARD OF TRADE UNIT.

IT has been stated that every substance consists of molecules or atoms and that these can be split into protons and electrons. To begin to understand what happens when an electric current flows, we must examine the behaviour of these atoms and molecules within the structure of a substance.

Continually in Motion

Even in a solid, the atoms or molecules, as the case may be, are in motion all the time, continually colliding with each other and moving away again. The speed of this random motion is a measure of the temperature of the substance. Incidentally, remembering this, you will the more easily be able to appreciate the important point that heat is a form of energy.

To understand the electrical facts, consider the atoms in a piece of copper. Each of these has the three inner shells full of the correct quota of electrons. In the fourth shell from the centre there is but one electron.

When the copper is in its usual solid state, the atoms are very near each other, so that at any one moment many of them are touching. The outer orbit of one atom then coincides with the outer orbit of the one it is touching. An electron at that point is the same distance from the nuclei of both atoms and is, therefore, subject to equal pulls from each.

In this condition, any slight disturbance can cause the electron to proceed, not on its original orbit, but on the orbit of the next atom. This happens constantly to millions of outer orbit electrons, and there is a continual haphazard transfer of electrons from atom to atom in all directions. Such electrons are said to be "free."

In Fig. 1a an attempt has been made to represent these free electrons.

Suppose that an electrical stress, or e.m.f., derived from a battery or generator, is applied to the piece of copper. This force is such that the copper has a surplus of electrons at one end and a deficiency at the other, and there is in between a state of tension trying to make electrons move towards the end that has a deficiency.

Drift in One Direction

When a free electron in the copper gets to its neutral position, it is no longer free to take any possible direction because it comes under the influence of the applied pressure. So it moves towards the positive end. Multiply this millions

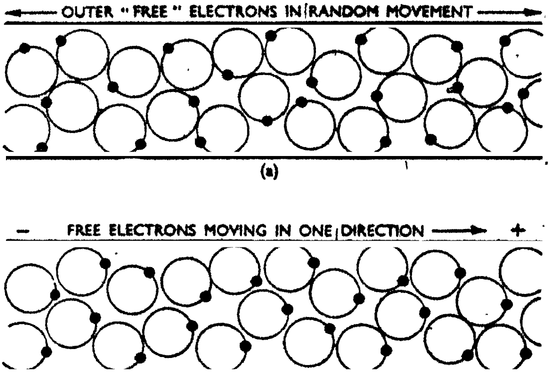

OUTER "FREE" ELECTRONS IN RANDOM MOVEMENT
(a)
FREE ELECTRONS MOVING IN ONE DIRECTION
−
+

Fig. 1. Imaginative diagram of the action of conduction of electricity through copper. At (a) there has been no applied electrical pressure, and (b) shows the drift of the electrons in one direction while the pressure is being applied and sustained. In an actual conductor there are millions of electrons to form the current.

of times and we have a steady drift of free electrons in one direction.

This drift is an "electric current." The greater the number of electrons reaching one end per second, the bigger is the current. In Fig. 1b this second condition is suggested.

When a substance allows this electron drift under the influence of electrical stress, we say that it is a *conductor*.

Most people know from everyday experience that some substances are good conductors and some are not. Why should there be this difference?

First, consider a gas. In a thin attenuated substance of this kind, the distance between any pair of atoms is so big, comparatively speaking, that collisions are relatively few and the opportunities for the transference of electrons from one atom to another very rare. All gases are, therefore, normally very bad conductors.

Conductivity in liquids is more complicated. First, it is necessary to understand that there are two kinds of liquid. There are substances which are liquid at normal temperatures, such as water and oils. There are also liquids which are solutions, that is, one substance is a liquid and in it has been dissolved another substance, itself solid or liquid. For example, salt can be dissolved in water to produce a liquid which is a solution. And in ninety-nine cases out of a hundred, when we speak of a solution, we mean one consisting of a substance that has been dissolved in *water*.

The two kinds of liquid must be considered separately. In the one which is itself a liquid at normal temperatures, the mechanism of conduction is the same as that in a solid. But the liquid is a sort of intermediate state between solid and gas, and the chances of atomic collision are less than in a solid and greater than in a gas.

Good Conductivity

Such liquids occupy a place in between solids and gases as conductors of electricity. One exception is mercury, which is very dense and has atoms close to one another. We can say, therefore, that mercury is a good conductor.

There is, moreover, a further complication occurring in both solids and liquids, which must now be considered. That complication is due to the fact that many substances consist of molecules moving about, not atoms. They are not elements but compounds.

Marble, for example, consists of molecules of calcium carbonate; and each of these has an atom of calcium, an atom of carbon, and three atoms of oxygen, all chemically combined into a compact unit in which the nuclei and electrons are securely held in a fixed pattern.

In the marble, there are no free electrons to respond to an e.m.f. and so it is a bad conductor. Any solid or liquid which consists of molecules, and some are much more complex than marble, is a bad conductor. Oils make a familiar example. Pure water is a bad conductor.

Liquids which are solutions, however, behave in a different way. When a substance is dissolved in water, the molecules break up into two parts, a process which is known as "dissociation."

Sometimes the separate parts are electrically neutral, and then the solution is a bad conductor, the mechanism being the same as for a solid. A solution of sugar is a good example of this sort.

When the dissociation is such that the parts are electrically charged, as with salt, sulphuric acid, and numbers of other substances, the behaviour under electrical stress is quite different. Then, the positively charged parts move towards the negative end of the applied e.m.f. and the negatively charged parts move towards the positive end. The parts are called "ions," because they travel.

The liquid is then a good conductor, though not as good as a solid consisting of atoms, such as copper. When a liquid behaves in this way it is called an "electrolyte."

Water from the water mains has substances dissolved in it which behave in this way, and so it is a conductor, unlike pure water.

Factors Involved

The conductivity of a substance depends, therefore, on whether it consists of atoms or molecules, on whether it is solid, gas, or liquid and, if the last, on whether it is an electrolytic solution. We cannot make a statement that all solids are better conductors than liquids, or all liquids better than gases, because of the many factors involved.

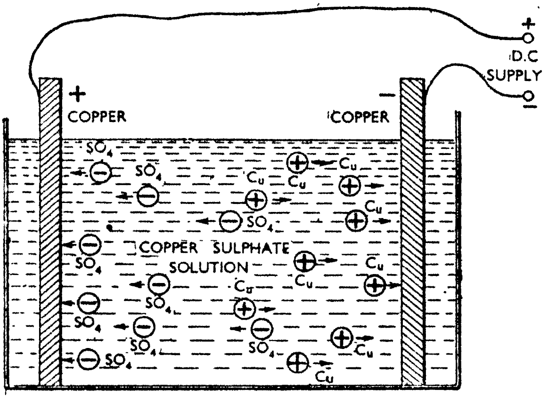
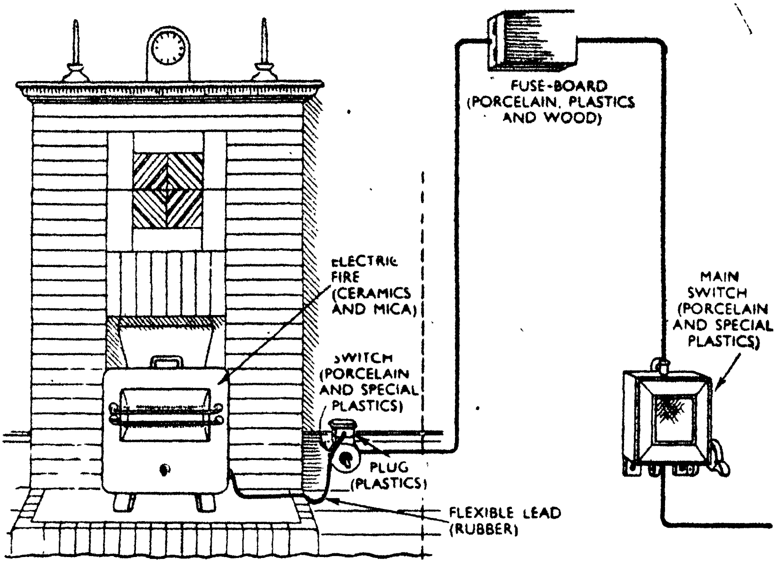


Fig. 2. Copper sulphate solution has split into ions which are travelling, under the stress of applied electrical force, in the directions shown.

Fig. 2 shows diagrammatically the action of conduction in an electrolyte. Examination of this shows that copper is being added to the negative electrode. This


FUSE-BOARD (PORCELAIN, PLASTICS AND WOOD)
ELECTRIC FIRE (CERAMICS AND MICA)
MAIN SWITCH (PORCELAIN AND SPECIAL PLASTICS)
SWITCH (PORCELAIN AND SPECIAL PLASTICS)
PLUG (PLASTICS)
FLEXIBLE LEAD (RUBBER)

OLD AND NEW INSULATING MATERIALS IN USE

Fig. 3. Insulating materials are employed to ensure that the current is confined to the conductors and the apparatus it operates. Above is seen where some of the more widely used ones are to be found in a type of electrical circuit which will be familiar to many readers. There are, nowadays, several other kinds of ceramic insulators besides porcelain and many plastic materials are employed.

suggests that we could measure the current in terms of the increase of weight of this electrode per second.

For the international standard, silver electrodes are used in an electrolyte of silver nitrate solution. The unit of current so measured is called the *ampere*, and it is that current which deposits 0·001118 of a gramme of silver in one second.

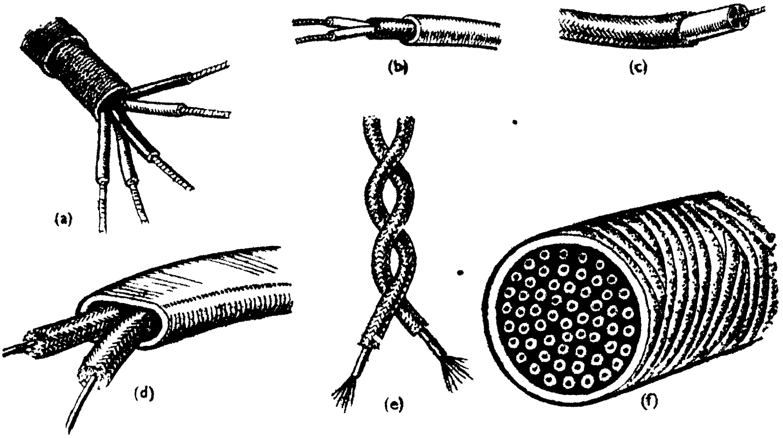
Insulators

Some materials are such bad conductors that when e.m.f.'s of the size met with in normal practice are applied, no measurable current results; these are called *insulators*. It is a relative term. For example, air is an insulator according to our definition, yet, under the giant stresses set up in a thunderstorm, long tracts of air become conductive, and then they pass currents of thousands of amperes.

Among the solid elements, the one which is the best conductor and offers least resistance to the passage of current is silver. Next comes copper, and this is the one most frequently used, in rod and bar and wire, for all electrical apparatus where good conduction is required.

Some of the familiar insulating materials are shown in Fig. 3. In recent years, new ceramics and plastics have greatly extended the list of such materials.

Before going further, it must be mentioned that the word "insulator" can be used in two ways. First, it may mean a substance that is virtually a non-conductor in the sense in which the word has been



CONDUCTORS AND INSULATORS IN COMBINATION

Fig. 4. (a) Cable of five conductors in extruded plastic sheaths, and all in a braided sleeve; (b) two conductors in extruded plastic, both in a metal braided sleeve inside an extruded plastic tube; (c) conductor spaced in centre of hollow tube of insulating material protected by braiding; (d) ordinary lead-covered twin, each conductor in rubber and cotton; (e) twin flex; and (f) telephone cable, lead outside and single conductors inside, each conductor covered with insulating paper.

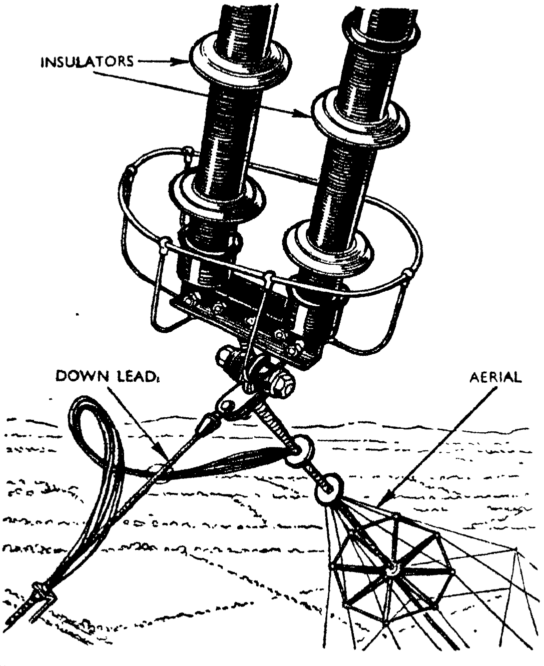


Fig. 5. Porcelain is the most widely used material for insulators that are exposed to the weather, for it is very resistant to the effects of the atmosphere. But it is a special, hard porcelain made of china clay, quartz and felspar from which are made, for example, wireless aerial insulators such as those shown in this drawing. High voltages are present in a transmitting aerial and these impose a considerable electrical strain on the insulators. Note how they are provided with flanges to increase the effective lengths of their surfaces.

used above. Secondly, it may mean a specially shaped object made of insulating material.

The verb "to insulate" really means "to separate or divide off," and that is what an insulator is used for in electrical work. It is employed to separate parts of a device or apparatus which must be in close proximity in space but not in electrical contact. Thus, we ensure safety and efficiency.

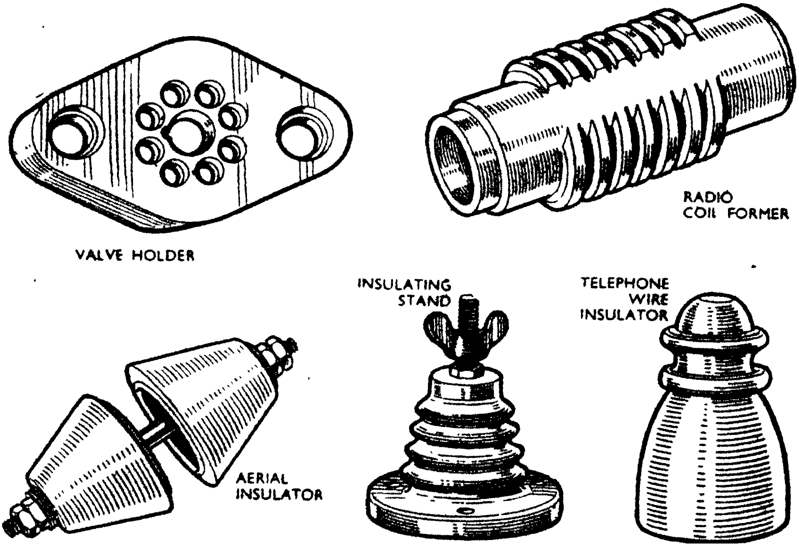
Use of Insulation

One or two examples will make this clear. Suppose we were to wind a coil of bare copper wire, the turns touching, on a cylinder of insulating material. Then, an applied electrical pressure would cause current to flow straight through from one end to the other by means of the contacts between adjacent turns. If we wish to make the current go through the whole length of the wire, i.e. round each turn, we must cover the whole length of it with an insulating material (Figs. 3-7).

Again, if the metal cables carrying the tremendously high pressures of our National Grid were hooked up on metal pylons, current would pass through these pylons to earth and so be lost; and any one touching such a pylon would be in danger. So we use carefully designed insulators of great mechanical and electrical strength to keep the cables away from the supports and the pylons.

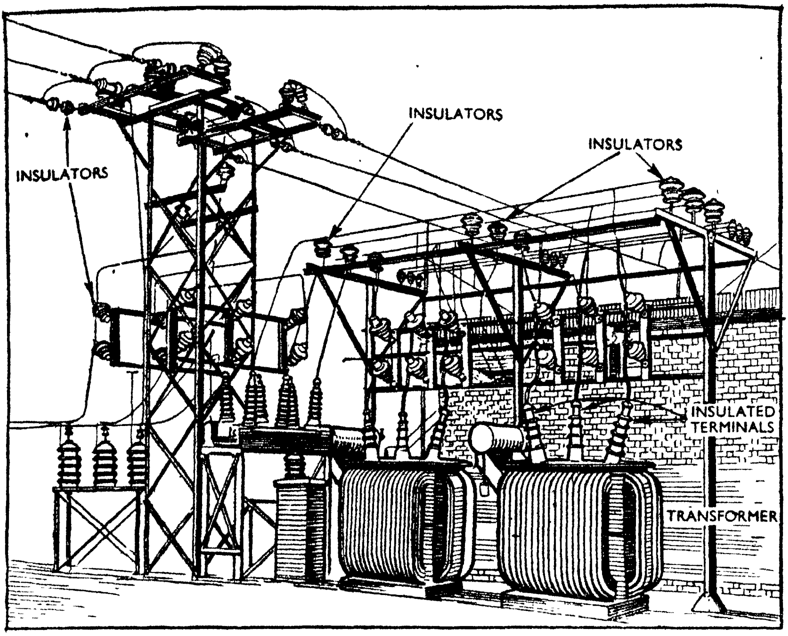
This brings us to the next important point. When conductors are joined together so that current can flow across the junction, the parts so joined must be in good metallic contact.

When all the parts of an apparatus are intended to remain fixed and permanent, it is best to solder



INSULATORS FOR SPECIAL PURPOSES

Fig. 6. Insulating units for which varieties of porcelain or steatite are frequently employed. The latter is a mineral which, after heat treatment, becomes very hard.



INSULATORS TO BE SEEN AT A SUB-STATION

Fig. 7. In the distribution of electricity, very high voltages are used and insulation is an important factor. Note the insulators used in this typical sub-station layout

all joints, remembering to use a flux made from resin to ensure that there is no corrosive action which might make a non-conducting film inside the joint, between the joined surfaces (Fig. 8).

Temporary Connections

For a temporary connection, a plug and socket joint can be used; or a terminal can be fixed on the apparatus and a tag put on the end of a wire. Then the tag can be inserted in the terminal and the screw top made fast. Without a tag, wire ends get broken and the fine wires of flex get frayed. A number of connectors are shown in Fig. 9.

When flex or other insulated wire is used, the end of the covering must be scraped away in order that the bare metal be available for insertion into terminal or plug.

The stage has now been reached in this discussion for the introduction of a word so far avoided for the sake of simplicity. That word is "circuit."

Examine Fig. 10a. A battery is shown being used to light a small electric lamp. In the battery, the chemical action piles up electrons on electrode *A* and creates a deficiency on the other electrode. This is the state of affairs which has already been described as a stress, or pressure, or e.m.f. It is caused by the great striving on *A* to get rid of its surplus electrons and the similar striving on the other electrode to recapture the ones it has lost. In the arrangement shown

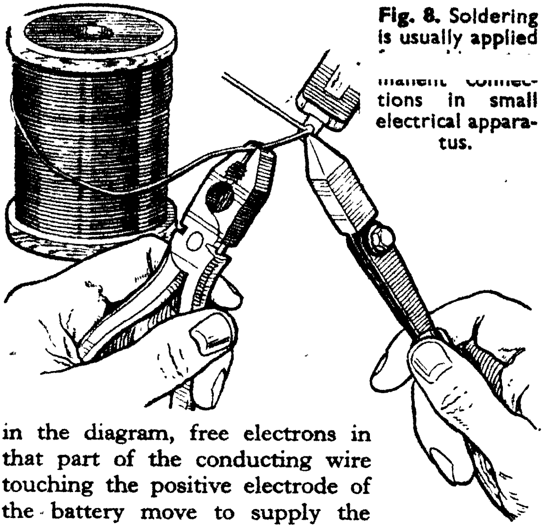


Fig. 8. Soldering is usually applied

manent connections in small electrical apparatus.

in the diagram, free electrons in that part of the conducting wire touching the positive electrode of the battery move to supply the latter's deficiency. More free electrons move in to make up the deficiency thus created in the conductor end. This is repeated in a very small space of time all the way

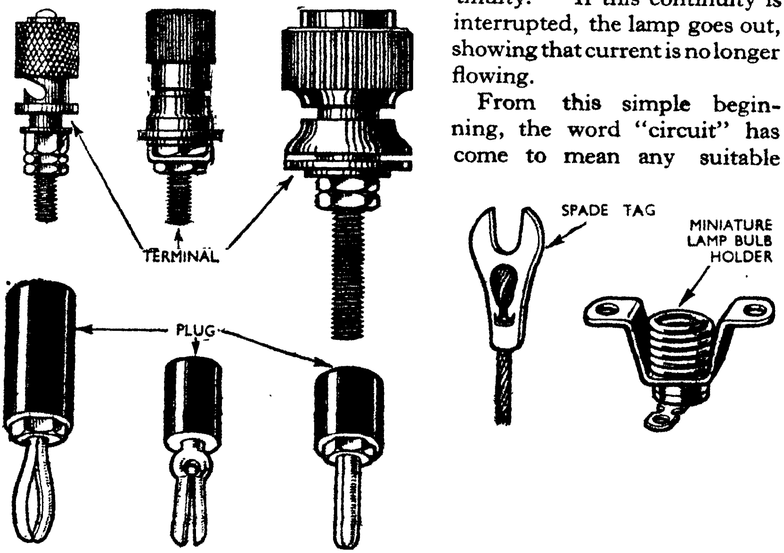
tor, through the filament of the lamp, back to the electrode *A*.

Continuity

In this way, electrons flow along the conducting wire from *A* to the metal casing of the little lamp, thence through the filament, out through the centre knob at the base, and so to the positive electrode.

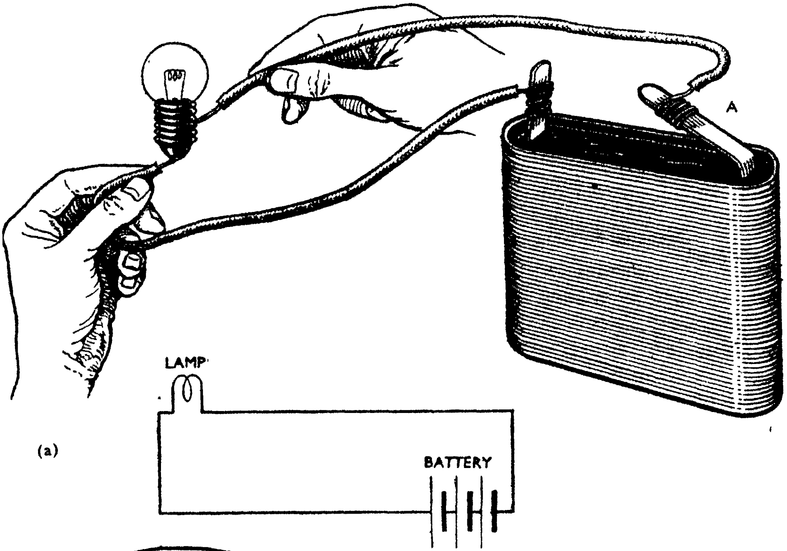
This is a very simple *circuit*, and we see that the word, in essence, means "electrical continuity." If this continuity is interrupted, the lamp goes out, showing that current is no longer flowing.

From this simple beginning, the word "circuit" has come to mean any suitable



USEFUL DEVICES FOR TEMPORARY CONNECTIONS

Fig. 9. Showing the standard items used in making connections to batteries and components where permanency is not necessary, and easy disconnection is useful.



arrangement of electrical apparatus in which current can flow. Some circuits are very complicated indeed. But if the source of e.m.f. is a cell, a battery, or a direct current supply of any other sort, there must be this continuity of conductor from one side of the source to the other if current is to flow.

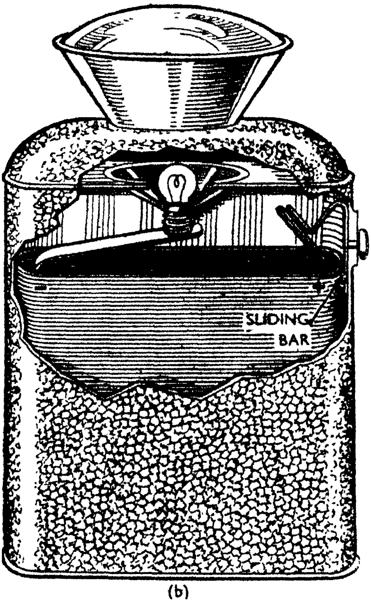


Fig. 10. At (a) is seen a simple circuit embodying a flash-lamp bulb and battery. The electron flow is from electrode *A*. In a flash-lamp (b) the circuit is completed through the switch and metal case.

Circuit Breaking

The arrangement of Fig. 10a would be very clumsy for continual use. A practical device is shown in Fig. 10b, which is an electric torch. The metal case forms not only a holder for the battery and lamp, but links them into a circuit complete with a device for making and breaking the connection as required.

Such a device is called a "switch," and is an essential part of any circuit. Everyone is familiar with the ordinary wall tumbler switch. The action of it depends on the operation of a small U-shaped piece of brass, which is caused to bridge a gap, and then the circuit is said to be switched on. The other operation is to remove the piece suddenly by a snap action, thereby breaking the circuit. Other designs of switch, with their circuit symbols, are shown in Figs. 11 and 12.

Circuit Symbols

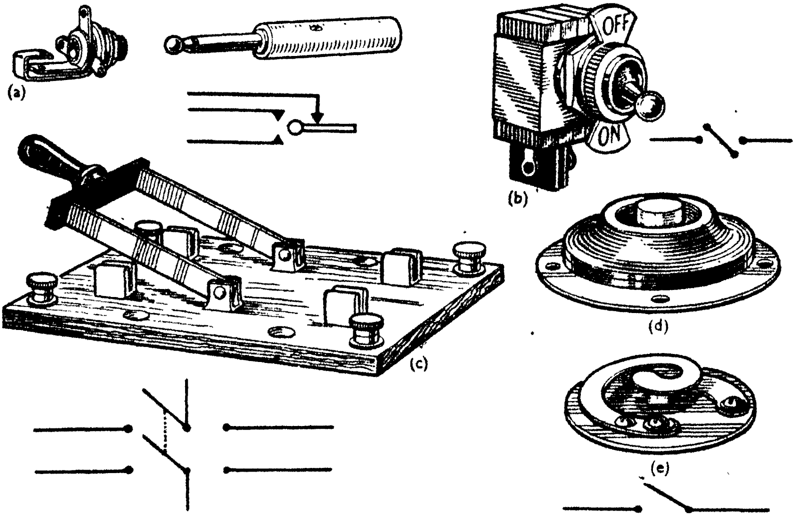
It will be appreciated that showing a circuit by means of pictures of the actual objects is a laborious process. To simplify the task, circuit symbols have been invented. These often illustrate the principle or general appearance of the piece of apparatus in as few lines as possible. Straight lines are used to show the connecting wires.

A single-pole single-throw switch and a double-pole double-throw switch are represented in Fig. 11, ignoring the actual appearance and type, whether rotary, knife switch, bell-push or what else. As far as a switch is concerned, we wish to know only how many contacts must be made simultaneously and how many positions of the switch are possible.

In Fig. 10a the circuit diagram for the arrangement is shown. Gradually, the symbols must be learned, and in some of the diagrams they will be shown in addition to the pictures of components.

Before leaving this discussion of conductors and circuits, a word or so can be added about units and instruments. As already stated, the unit of current is the ampere. The electrical stress, or pressure, or the e.m.f., has a unit which can be mentioned here and then dealt with in more detail later on. It is the *volt*, from which is derived the very common term "voltage."

Measuring instruments are the subject of Chapter 12, but some



SWITCHES AND SWITCH SYMBOLS

Fig. 11. (a) Jack and plug; (b) toggle switch; (c) double-pole, double-throw knife switch; (d) ordinary domestic type of bell push; (e) bell push, cover removed.

reference to meters for measuring current and voltage must be made here. The instrument for measuring current is the ammeter, that for measuring voltage is the voltmeter. Each is represented in circuit diagrams by means of a circle inside which is printed A, if an ammeter; V, if a voltmeter.

Use of Prefixes

Sometimes current or voltage is large, sometimes very small. A measuring instrument with the appropriate scale is used, according to the size of the current or voltage. The prefix "micro," shown by the Greek letter μ ("mu"), is added to mean "a millionth of." For example, 20 microvolts means 20 millionths of a volt. The appropriate instrument is a microammeter or microvoltmeter.

The prefix "milli," shown by the letter m, is added to mean "a thousandth of." For example, 36 milliamperes means 36 thousandths of an ampere. The appropriate instrument is a milliammeter or a millivoltmeter.

The prefix "kilo," shown by the letter k, means "thousands of." An example of this will conclude this very short summary: 50 kV means 50 kilovolts or 50,000 volts.

Great care must be exercised in the use of instruments, for by using one of the wrong sensitiveness we may damage it irreparably.

Resistance

The reluctance of atoms and molecules to let electrons get free to drift towards the positive pole of the applied voltage is called *resistance*. Copper has plenty of free electrons and is a good conductor. Another way of stating this is to say that copper has low resistance.

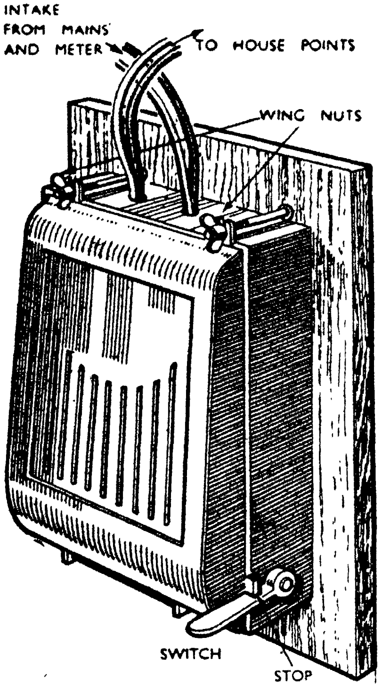


Fig. 12. Ironclad mains switch, showing the stop which prevents the front opening while the switch is "on."

In some materials, the applied force has actually to tear electrons from their orbits to make them free, and the resistance of such materials is then said to be high.

The unit of resistance is the *ohm*. It has been agreed internationally as the resistance of a column of mercury 106·3 centimetres long at 0 deg. C., of uniform cross-section and weighing 14·452 grammes (Fig. 13). The abbreviation is Ω, the Greek omega.

In order to avoid very small fractions for low resistance values, a smaller unit, the *microhm*, is used, a millionth of an ohm. In the case of insulators, the resistance is high and a large unit is used, the *megohm*, a million ohms. The abbreviations are respectively μΩ and MΩ.

The resistance of a conductor or insulator depends first and foremost on the material itself. It also depends on the dimensions, the length and the cross-sectional area. It increases in direct proportion to the length. For example, 13·5 in. of No. 26 Eureka have a resistance of 1 ohm; 27 in. a resistance of 2 ohms; 40·5 in. 3 ohms, and so on.

On the other hand, resistance decreases with increase of cross-sectional area. This is readily understandable, for there are more atoms to be affected and a greater likelihood of free electrons.

Wire Tables

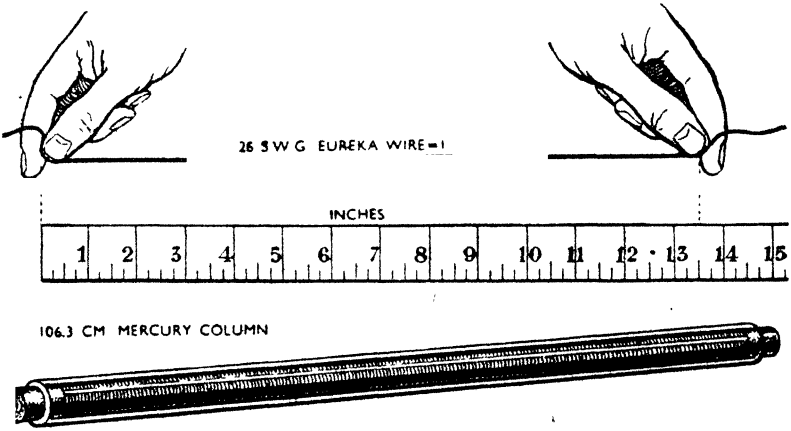
The engineer, when he wishes to find the resistance of a conductor, refers to a Wire Table where the resistance of so many yards is set down against the gauge (diameter) of each wire.

When he intends to use an unusual conductor for which tables are not available, he first looks up the resistance of a piece of the material 1 in. long and 1 sq. in. in cross-sectional area; this is called the *specific resistance*, or the *resistivity*. He then multiplies this by the length of the conductor in inches and divides by the cross-sectional area in square inches. The answer is the resistance of the conductor in microhms.

Practical Example

As an example, the resistance of the cable in Fig. 14 can be calculated. Assume the distance from house to generator is 2 miles, the cable diameter is 0·5 in. and the resistivity of copper is 0·67 microhms per inch cube.

It must be remembered that there are altogether four miles of cable (go and return). There are 63,360 in. in one mile. A diameter of half an inch gives the cross-sectional area as approximately 0·2 sq. in. By the following calculation the resistance is found to be:



MEASUREMENTS OF RESISTANCE

Fig. 13. Rough standard for an ohm is given by 13·5 in. No. 26 gauge Eureka wire. The international standard is a column of mercury 106·3 cms. long at 0 deg. C., of uniform cross-section and weighing 14·452 gms. This is shown in bottom diagram.

$0{\cdot}67 \times 4 \times 63{,}360 \div 0{\cdot}2$
$= 2{\cdot}68 \times 63{,}360 \div 0{\cdot}2$
$= 169{,}804{\cdot}8 \div 0{\cdot}2$

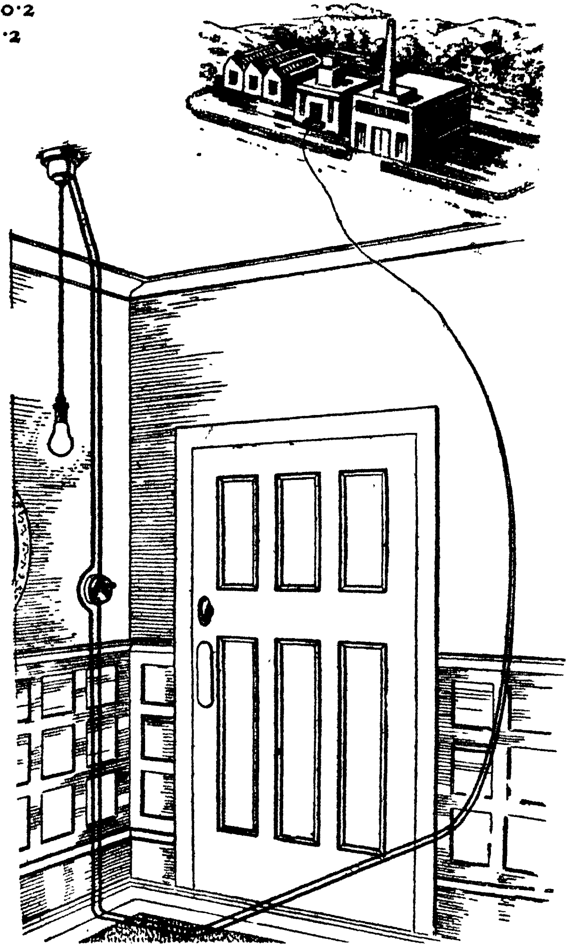
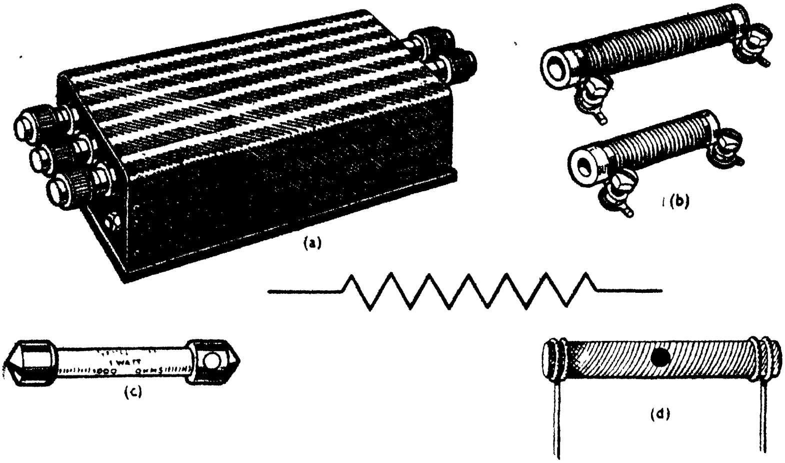


Fig. 14. Showing, in pictorial form and without fuses, meter, etc., the fundamental circuit between power station and a domestic light bulb.

Now these are microhms, so the figure must be divided by one million to bring the answer to ohms. Thus:
Resistance in ohms
$= 849{,}024 \div 1{,}000{,}000$
$= 0{\cdot}85$ (approx.).

In so far as even the best conductors possess resistance, it is a disadvantage because energy has to be used to drive the current. On the other hand, without the high resistance of insulators most circuits would be impracticable. In addition, by making components of high resistance and putting them in circuits, we can concentrate the resistance where it is required and can vary it in order to regulate the current. Such components are called *resistors*. Special materials must be sought for resistors. The best known of these is an alloy of nickel and chromium, one trade name for which is *Nichrome*; this has the advantage of high resistance and, which is also important, high melting point. Another alloy is *Eureka*, made of 60 per cent copper and 40 per cent nickel. The resistivity of Nichrome is more than twice as much as that of Eureka, and this latter is twenty-eight times as resistive as copper.

Resistors can be made of Nichrome or Eureka or other alloy. When high resistance is required in a very small space, the material used is a composition whose base



RESISTORS IN GENERAL USE

Fig. 15. (a) Resistor for carrying heavy current; (b) is a smaller wire-wound pattern; (c) and (d) are of high value, the latter being colour-coded. A non-variable resistor is indicated in theoretical circuit diagrams by a zigzag line as shown.

is carbon. One type of composition resistor is brightly coloured and is seen inside radio sets; the colouring is to show the resistance value according to an agreed code. The body colour indicates the first figure, the tip colour the second figure, and a dot shows the number of noughts to be added to the first two figures.

The code is: Brown 1, Red 2, Orange 3, Yellow 4, Green 5, Blue 6, Violet 7, Grey 8, White 9, Black 0. Its purpose is to provide an immediately recognizable visual indication without the necessity of minute printing which might be worn off

It should be noted in passing that the word "resistor" is used for the component. Those illustrated in Figs. 15 and 16 should not be called "resistances," the latter word, in the singular, being retained for the quality already described. When a circuit has distributed resistance not concentrated in any component, the symbol used in the diagram is, however, exactly the same as the one for a resistor.

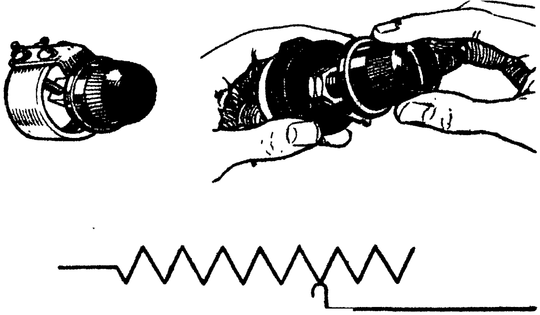
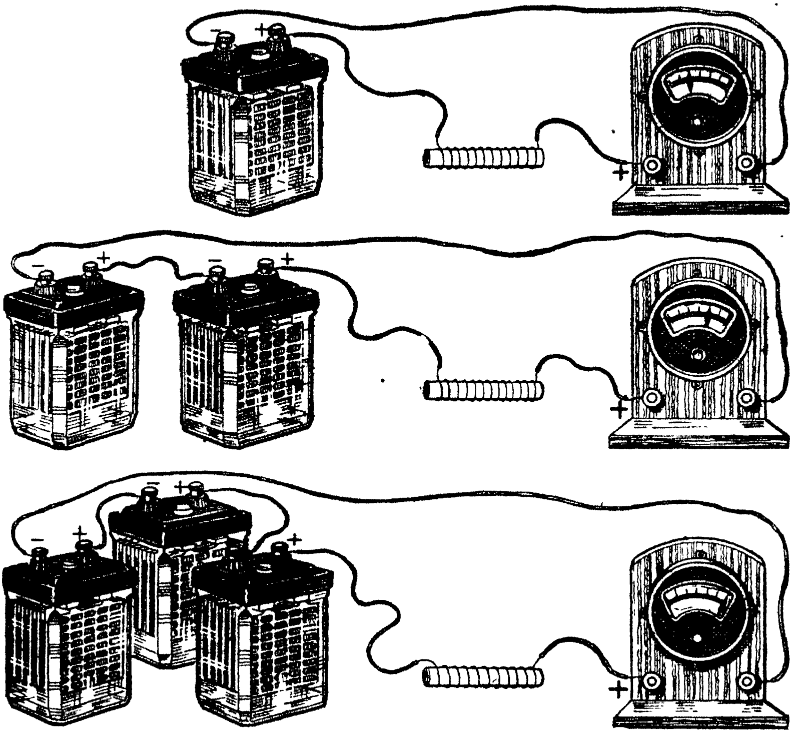


Fig. 16. Two variable resistors of the small rotary type which may be wire-wound or of carbon composition. The lower sketch illustrates how a variable resistor is shown in circuit diagrams.



HOW CURRENT AND VOLTAGE ARE RELATED

Fig. 17. Using about 52 in. of No. 26 gauge Eureka wire, wound with spaced turns on a porcelain or asbestos tube, the ammeter readings should be 0·5, 1, or 1·5 A, respectively, when connected to two-, four- or six-volt accumulators.

Some resistors are made variable in value by means of a slider or rotary contact; the latter being shown in Fig. 16.

Simple Experiment

The most fundamental electrical "law" of all has now been reached and there is a simple experiment which will help to make this clear.

The circuits are shown in Fig. 17 and the details given. First, using one accumulator cell, the ammeter reads about 0·5 A. With another accumulator cell in series with the first, the ammeter shows approximately 1·0 A. With a third accumulator cell the ammeter reading is 1·5 A. Now let us compile a little table of results:

Volts	*Amperes*
2	0·5
4	1·0
6	1·5

We see that as the voltage is increased, so the current increases, *and in the same proportion*. In other words, the current is directly proportional to the voltage. How can we express the amount of proportionality? Simply, by dividing the volts by the amperes. The answer in the above case, is 4 each time.

If the resistor were wound with

104 in. instead of 52 in. of No. 26 Eureka, and the whole experiment was repeated (Fig. 18), the results would be (approximately):

Volts	*Amperes*
2	0·25
4	0·5
6	0·75

Again, the current is directly proportional to the voltage. But if we divide the volts by the amperes, we get the answer 8 each time. So the value of the proportionality has increased.

What was changed in the second set of experiments? The answer is, the resistance. In some way the ratio of current to voltage is something to do with the resistance.

Now we come to the most cunning part, due to the ingenuity of the men who sat at the international conference which standardized the ampere and the ohm. They agreed that current was directly proportional to the voltage, and they agreed that this proportionality depended in value on the resistance. So they decided that they would arrange a standard for the volt.

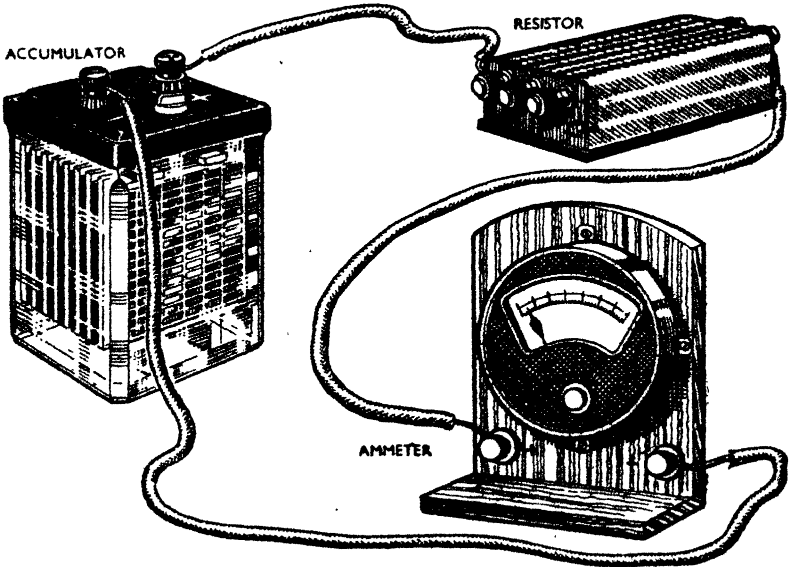
They said that if a current of one ampere flowed through one ohm, then the applied voltage to achieve this should be called the volt and used as the standard.

Thus we get the law:

Current in amperes = applied pressure in volts divided by the resistance in ohms.

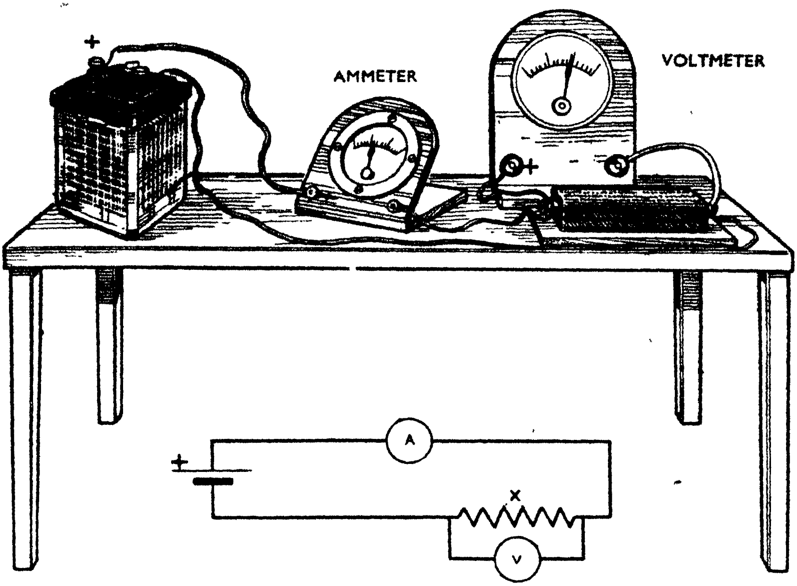
This is the modern form of the law known as *Ohm's Law*, because Professor Ohm did the work which first established the proportionality we have discussed. The unit of resistance was also named after him.

The law can be written in two other ways. Perhaps we know the



OHM'S LAW IN PRACTICE

Fig. 18. Two of the constants of this simple circuit are known. The secondary cell provides a pressure of 2 volts and the current is indicated by the meter. By means of Ohm's Law the resistance can be calculated.



PRACTICAL METHOD OF MEASURING RESISTANCE

Fig. 19. This circuit is similar to the one shown in Fig. 18, but a voltmeter is added to provide measurements of voltage. As the meters indicate the current flowing through and the voltage across the resistance (x), its value can be calculated.

current and the resistance but do not know the volts. Then we can find them from the law, but must use it this way:

Volts applied = current in amperes multiplied by the resistance in ohms.

On the other hand, we may be able to read the amperes and the volts and wish to calculate the resistance in ohms. Then:

Resistance in ohms = applied volts divided by the current in amperes.

Using symbols I for current in amperes, E for e.m.f. in volts, and R for resistance in ohms, we can write Ohm's Law in its three equivalent forms as:

$$I = \frac{E}{R}; \quad E = I \times R; \quad R = \frac{E}{I}.$$

Examples:

A fire has a current of 5 A through it when connected to 200 V mains. What is the resistance of the fire winding? Answer: 200 divided by 5 = 40 ohms.

This method is the basis of most practical ways of measuring resistance, one of which is shown in Fig. 19.

A lamp has a resistance of 1000 ohms and is lit by 200 V. What current is flowing? Answer: 200 ÷ 1000 = 0·2 A.

Ohm's Law is Fundamental

Once this law is grasped, we are in a position to do most calculations on circuits supplied by batteries or D.C. mains. It is fundamental.

We must be very careful to use our units correctly. For example, when we apply 2 V to a resistor, if the current is so small that we have

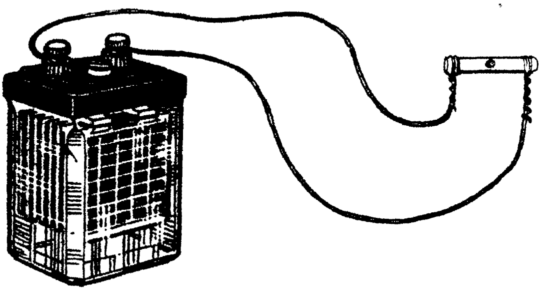


Fig. 20. Connecting an accumulator giving 2 V to a resistor of 100 ohms results in a current flow of 20 mA.

to measure in milliamperes, and is, in fact, 5 milliamperes, then, if we try to apply Ohm's Law in the way shown above we shall not get a correct answer. So the milliamperes must be turned into amperes by dividing by 1000. Then the resistance = 2 ÷ 0·005 = 400 ohms.

See Figs. 20 and 21 for additional examples.

When electricity flows in a circuit, the voltage across any small part of that circuit will not be equal to the applied e.m.f. For example, in the circuit shown in Fig. 19, part of the voltage is used up in overcoming the internal resistance of the secondary cell and part in the ammeter. So if the cell gives 2·0 V, we may find that the voltmeter registers but 1·8 V.

Potential Difference

For the voltage "dropped" across any component or appliance in a circuit we use the expression "potential difference," usually abbreviated to p.d. In the simple examples already given, we have kept to simple circuits where the e.m.f. is plied direct to the onent. Then the p.d. across the component is equal to the applied e.m.f. But in more complicated circuits, where several components are used, Ohm's Law can be applied to any one part if we remember that we are concerned only with the p.d. across it and not that across the whole circuit.

For example, join a lamp of 1000 ohms resistance in series with another of 2000 ohms and then apply 200 V to the whole circuit. Then a p.d. of about 67 V is produced across the first lamp and about 133 V across the second. If we wish to calculate the current in the second lamp we must divide, not 200 V, but 133 V, by 2000.

Voltage Drop

The resistance of the cables illustrated in Fig. 14 was calculated to be 0·85 ohm. Let us suppose that, when we switch on every appliance we have in the house, the current altogether is 20 A. Then the p.d. across the cables (half on the outward journey and half on the return) is 20 × 0·85 = 17 V. These volts are lost in the cables and so are not available at the house intake.

If the generator is producing 240 V, the house-owner is getting only 223 V. This drop in the cables

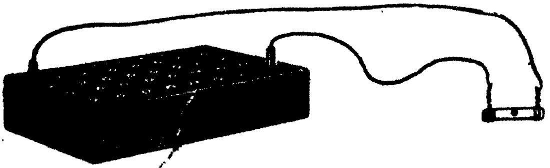


Fig. 21. When a H.T. battery of 120 V is joined to resistor of 6000 ohms, current flow is also 20 mA.

has to be allowed for by the supply engineers. When supplies have to be distributed over wide areas, the volts have to be boosted up at substations in order to make sure that consumers will get something near their allotted mains volts.

Electrical Measurements

Electrical pressure is measured by means of a voltmeter, as already stated. But a few words about meters are necessary before we go further, in order to make certain points clear.

Essentially, there is no difference in practice between an ammeter and a voltmeter. The maker takes a milliammeter and adds resistance in series to create a voltmeter and resistances in parallel to make an ammeter. But these added parts are usually inside the casing, and on the outside the only signs of difference are the words "amperes" or "volts" on the scales.

The instrument may be as small as a watch or as big as the face of a grandfather clock, and it may be constructed with base flanges for bolting it to a panel, or the front may be larger than the main instrument and supplied with holes, and then the instrument is sunk into a large hole on a panel and made firm by means of bolts through the holes provided (or ordinary screws if the panel is wood).

In large factories and power stations, the panels are many feet long and several feet high, and are made of slate surfaced with a glazed enamel. For laboratory and experimental work, the panel is usually wooden and is mounted either vertically or sloping slightly backwards on a wooden base. The connections are then brought to their respective terminals on the panel.

On one point there *is* a difference between voltmeter and ammeter; that difference, a very important one, is the method of connection. An ammeter (or milliammeter or microammeter, as the case may be) is always connected in series in the circuit in which we wish to measure the current. But a voltmeter is always connected in parallel across the component whose voltage we wish to know.

The meaning of series, end on end, and parallel have already been explained in connection with cells. An examination of the illustrations will make this point clear, especially Fig. 19, where an ammeter and a voltmeter are in the same circuit. If we were to change over the instrument positions in that circuit, the ammeter would merely record the bit of current going through its own branch and not the main current, and the voltmeter would record the voltage across its own resistance and not, what we want to know, the volts across the resistor provided.

Multi-range Meters

Many instruments have multiple connections. These are for providing many ranges. We must understand that any one instrument, a voltmeter, shall we say, has the range allowed by its construction, and no more. For example, 5 V applied to it may throw the needle to the very end of the scale. It is then said to have a range of 5 V. Now, if we apply, say, 25 V to it, the needle will swing violently over to the stop provided and the inner part may be burned out.

It might be thought that the solution is to make an instrument with a very large range. But what happens if we do so? Why, the scale divisions are so small that we cannot read anything less than about 0·5 of a volt with any accuracy, and the moving part, in any case, is far too heavy to show any reading at all if, say, 10 millivolts are applied.

So there must be one instrument for every range. But, instead of going to the expense of having many instruments, one of very low range can be taken, and then, by means of switches or plugs and socket connections, bringing different series or parallel resistors into circuit, the range can be extended.

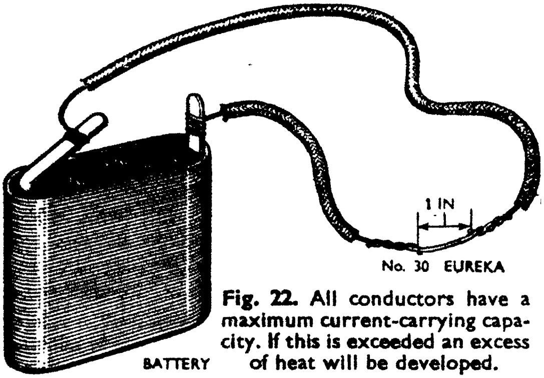


Fig. 22. All conductors have a maximum current-carrying capacity. If this is exceeded an excess of heat will be developed.

Details of measuring instruments are given in a later chapter and at present we must turn back to the nature of current to study one of its most important characteristics.

Heating Effect

Whenever an electric current passes through a conductor, some heat is generated. A very simple experiment, illustrated in Fig. 22, will show this. The Eureka wire gets red hot and melts.

It can be understood, in a very general way, how this heat is made. Atoms and molecules are in motion all the time. The faster they move, the hotter is the substance, and the more of them there are in such motion, the greater is the total heat energy.

When an e.m.f. is applied to a conductor, the free electrons, if any, are made to drift towards the positive end of the applied pressure. If there are not any free, then the applied force has to be big enough to tear some from their orbits before any current flows.

When current is passing, there must be atoms which are temporarily short of electrons and are positively charged. These will try to travel in the direction opposite to that taken by the electrons. Therefore, the total motion of atoms is increased and the speed of any atom is also changed because to its random motion is added that due to the applied electrical force. Therefore, the temperature rises.

This heating is *always* associated with current. We cannot have current without heat as well. This is often a considerable nuisance and we may have to take steps to lessen the ill-effects. We do this by using conductors of low resistance and by arranging adequate air cooling or even water cooling.

As most of us know, in the ordinary house installation there are two sets of wiring and two meters, one for "power" and one for "lighting." There is no difference whatever between the two supplies as they come into the house; in fact, they are in the same cable. But, inside the house, wires leading to points to be used for fires and cookers and the like are thicker than those for lighting points. The "power" wiring has lower resistance and can carry the high currents used without heating the surroundings or charring the insulation.

Concentrated Energy

Heat is a form of energy, and a very necessary one to all of us. It can warm our bodies, cook food, press clothes, boil water and so on. Instead of considering the heating effect of a current as an evil, we may think of it as beneficial. But, in that case, we must design our appliances so that the heat is concentrated in the right place and under control.

There are many devices wherein this localization and control of the heat are effected. The basis of them is special resistance wire which can be made red-hot without melting or suffering any deterioration; and the high resistance allows us to concentrate the amount of power we need into a small space.

This is a point sometimes difficult for students to grasp. If resistance, they think, is opposition to current, surely the best sort of appliance would be one made from material of low resistivity. But let us consider the catches in this reasoning.

Copper is the best conductor in common use. If we applied 200 V to a short length of this, the current would be enormous. Our domestic wiring is arranged to take only about 15 A and the heavy rush of current would overheat the wires and burn out the system. The appliance, lamp, fire, or cooker, must have a resistance high enough to reduce the current to a safe amount. At the same time, most of the resistance of the whole circuit is concentrated in the appliance and most of the heat is just where it is wanted (Fig. 23).

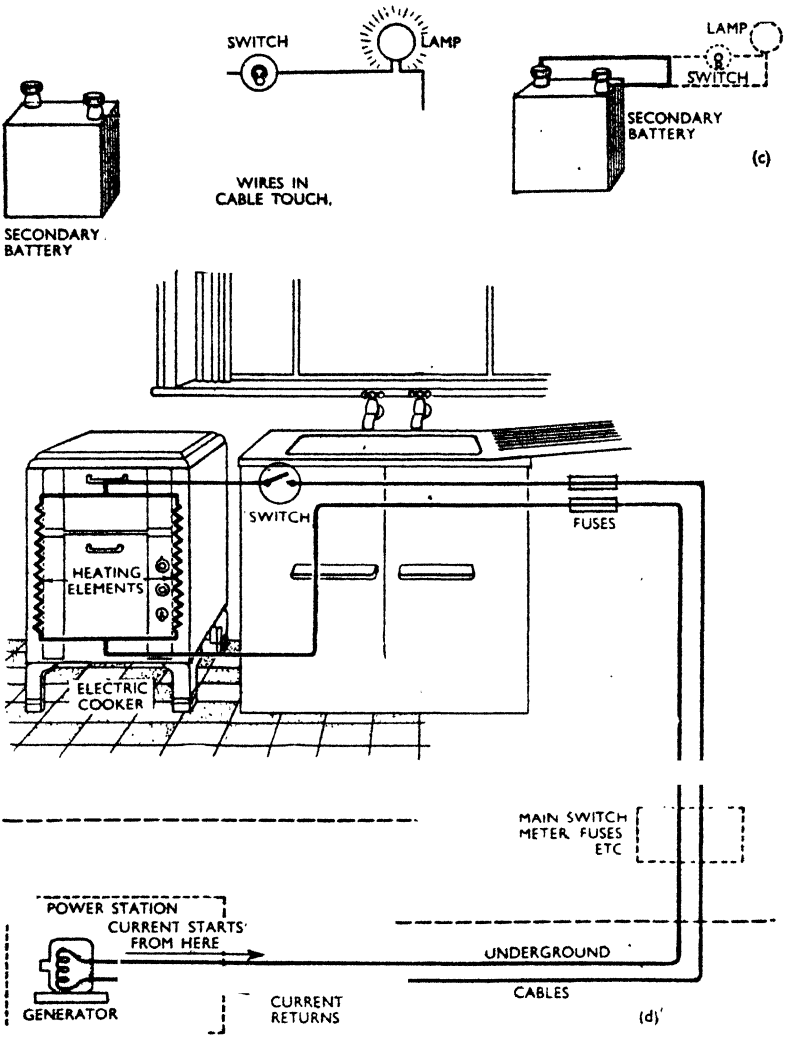
Before going further, there is another property which must be discussed. Let us imagine two houses in different districts. One man in one house has an electric fire which he knows consumes 5 A, his mains voltage being, say, 105. A second man in the other house is on, say, 210-V mains, and purchases an electric fire of the correct rating, and then finds that it consumes also 5 A when he makes a test with an ammeter in the circuit. Both are using 5 A. Which man pays the bigger electricity bill?

The answer is, that the second man pays twice as much for using his fire as the first man (assuming the same scale of charges, of course). The current alone is not a sufficient indication of the actual energy consumed and paid for. Nor is the voltage, though we might think so from the above example. For instance, if the second man finds that the current taken is 4 A, he will still pay a bigger electricity bill than the first.

Unit of Power

There must be some way of finding the actual energy consumed. There is; first, we must know the *power*, which is defined as *the rate of using energy*. In electrical calculations, the unit of power is the *watt* (W) and it is obtained by multiplying the volts applied by the current driven.

In the above example, the first man uses a power of 5 × 105 = 525 W. The second man uses 5 × 210 = 1050 W. The total energy consumed must depend,



PURPOSE OF CONDUCTORS IN CIRCUITS

Fig. 23. Conductors convey the current from the source of the supply of electricity to the apparatus it is desired to actuate. Obviously the best material for them is one which offers the least resistance, is relatively inexpensive and has desirable mechanical properties. Copper meets these requirements and, therefore, is widely employed. The switch in the simple circuit at (a) makes or breaks one of the paths provided for the current. Should the insulation of the conductors be faulty, with the result that they come in contact as at (b), a short-circuit occurs (c). Reference to (d), which illustrates in simplified form the connections to an electric cooker, reveals that even in a relatively complicated circuit, the purpose of the conductors is merely to convey the electricity to where it is required to do work.

also, on the time for which the power is used. (In the example it was assumed that both men used their fires for the same length of time.)

The unit of electrical energy for practical purposes is the *Board of Trade Unit* (B.T.U.) and is the energy represented by the consumption of 1000 W in one hour, and so is sometimes called a kilowatt-hour.

A 100-W lamp uses up one B.T.U. in ten hours, because 10 hours × 100 W = 1000 watt-hours, or 1 kilowatt-hour.

Now to get back to the subject of electrical heating. The heat generated by a current is directly proportional to the power and the time, i.e. the energy consumed. A boiling plate rated at 1600 W will, therefore, act twice as quickly as one rated at 800 W, other things, such as dimensions, saucepan size, etc., being equal.

Typical Wattages

The average wattage for an electric iron is 500, the actual value depending on the size. Electric fires range from the bowl fire at about 500 W to the largest vertical fire at 3000 W. Kettles average from 250 to 300 W per pint capacity.

There is one very common effect of electric heating with which everyone is familiar; that is, the production of light by heating a conductor until it is white hot. The first conductor used for this purpose was made of carbon, but it had a short life. Tungsten was an improvement.

The filament was enclosed in a glass bulb and the air pumped out to stop the filament burning away. This was the vacuum lamp. Later on, a still higher temperature was reached, and a more intense light emitted, by winding the filament in a close spiral and putting into the bulb a gas which will not combine chemically with the tungsten. Thus was produced the gas-filled lamp. All the stages are illustrated in Figs. 24 and 25.

Fuses

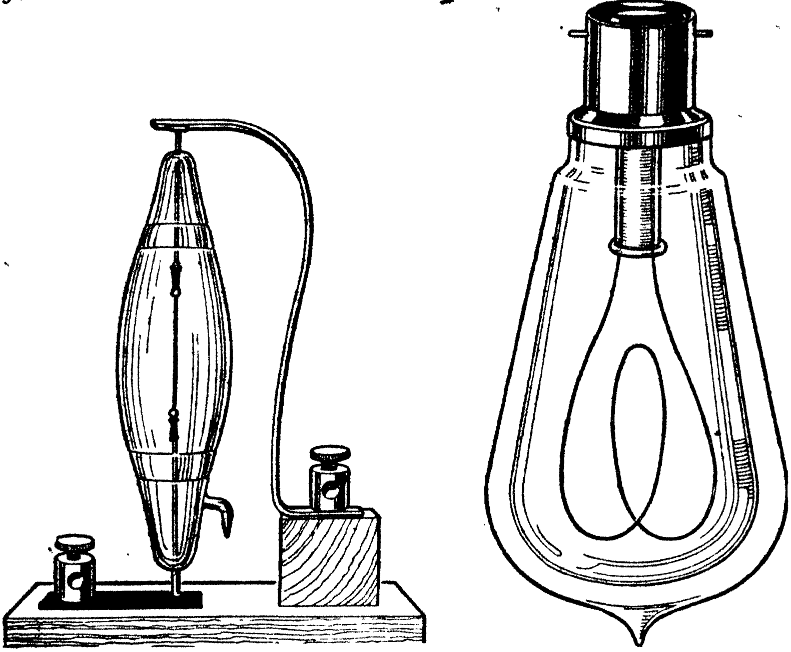
The melting away of a metal when heated is also utilized in circuits today. A wire of tin or, more usually, copper or silver, is included in a circuit as a safety device. When the current reaches a value approaching the limit for the wiring, then the piece of wire melts and so the circuit is broken. A wire used in this way is called a *fuse* (Fig. 26).

A fuse is a safety device. The diameter of the wire is chosen so as to burn out at a specified value of current. In house wiring, we usually employ fuses of two strengths, a 5-A fuse and a 15-A fuse, the former for the lighting circuits and the latter for the "power" circuits. These fuses "blow" at currents slightly below the rated current value and save our house wiring and any appliance we may be using from the overheating which would be caused by an excessive current.

In other circuits, power plant and radio sets, for example, fuses of different ratings and specialized designs are used.

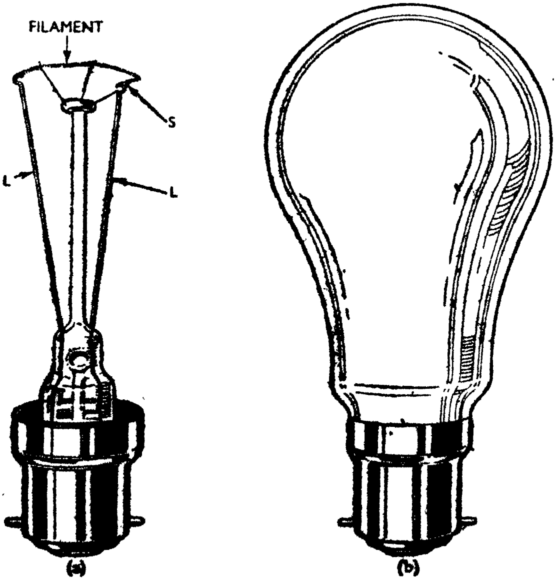
It is essential for us to be able to replace a "blown" fuse. So it is fixed on a holder which is held in the circuit by spring or other mechanical contacts. We can easily remove the holder and replace the fuse.

Now we are talking again of currents, we can discuss what



EARLY STAGES OF THE ELECTRIC LAMP

Fig. 24. (Left) First electric lamp ever exhibited ; made by Joseph Swan in 1878. The carbon filament lamp (right) was an early commercial development.

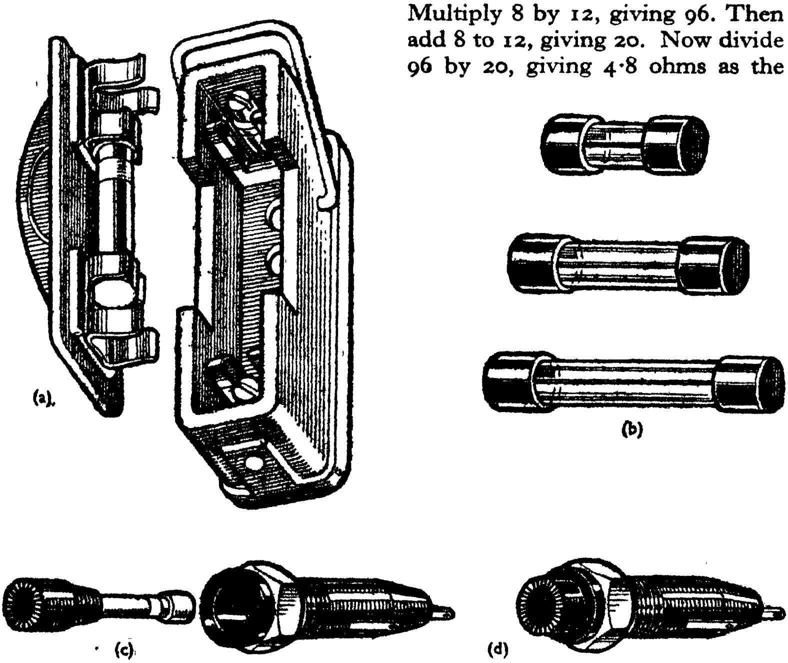


(a) (b)

Fig. 25. Modern lamps have fine spiral filaments of tungsten. The inner construction is shown (a), with the supporting wires (*LL*) which also carry the current to the filament; (S) is an anchor support. (b) The filament is usually enclosed in a gas-filled glass bulb. It will be noticed that the filament is in the form of a close spiral instead of being straight wire as in earlier electric lamps. In some of the latest types the spiralled wire is itself made into a spiral, and with "coiled coil" filaments, as they are termed, high efficiencies are achieved.

happens when resistors are connected up in different ways.

When two or more resistors are joined in series, the total resistance is greater than for either of the resistors, because resistance, as we have said, depends on the length of conductor. We merely have to add the values together. For example, two resistors, one of 80 ohms and one of 60 ohms, joined in series, will make a total effective resistance of 140 ohms.



SAFETY DEVICES IN THE CIRCUIT

Fig. 26. (a) Cartridge fuse and holder; (b) small wire fuses having glass covers. (c) and (d) plug type, for mounting on panel, showing fuse out and in socket.

Resistors in Parallel

When resistors are joined in parallel, however, the conductor path is, in effect, being increased in cross-sectional area, and the total resistance is reduced. This time the calculation of the result is not so simple. We must take the two values and multiply them by each other. Then we must add them together and divide this answer into the first one (Fig. 27).

Example:

Two resistors, whose values are 8 ohms and 12 ohms, are in parallel. Multiply 8 by 12, giving 96. Then add 8 to 12, giving 20. Now divide 96 by 20, giving 4·8 ohms as the effective resistance of the combination. If there are more than two, we can first of all find the effective resistance of two of them, then use this result and combine it with one of the remaining ones by the same rule, and so proceed through all the resistors. An alternative is to use the following formula:

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3}, \text{ etc.}$$

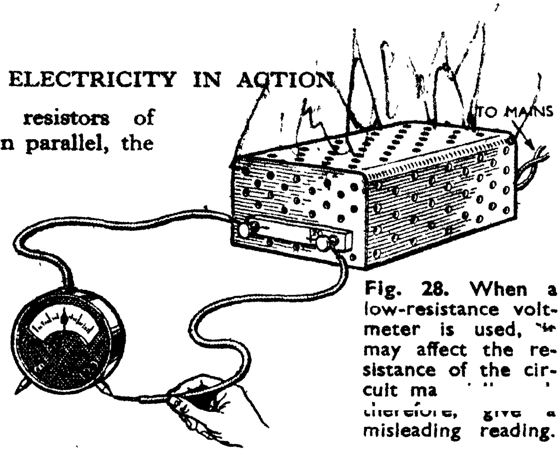


Fig. 28. When a low-resistance voltmeter is used, it may affect the resistance of the circuit ma [illegible] therefore, give a misleading reading.

Incidentally, where resistors of the *same value* are in parallel, the total resistance is the value of one divided by the number in parallel. For example, three 9-

value of 9 ÷ 3 = 3 ohms. We can pro-

sult of adding one resistor in parallel with another. Let us suppose that we have a resistor of 10 ohms. First put 10 ohms in parallel. The result is 5 ohms. Now remove the second 10 ohms and put instead one of 100 ohms. The combined result is now 9·1 ohms.

Paralleled Resistance

Remove the 100 ohms and substitute 1000 ohms. The combined result is now 9·9 ohms. We can summarize by tabulating the results.

We see that the higher the resistance added in parallel, the less is its effect in lowering the original value.

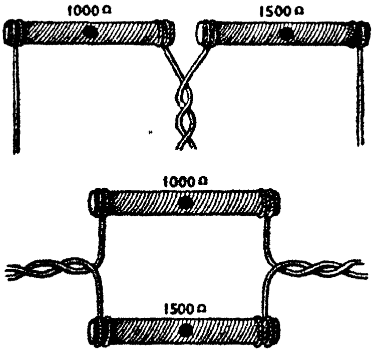


Fig. 27. Resistors joined in series (top) are equal to the sum of their values, but when they are joined in parallel (below), the total resistance is reduced, in this case to 600 ohms.

Resistance in ohms	*Added resistance in parallel in ohms*	*Result in ohms*
10	10	5
10	100	9·1
10	1000	9·9

A voltmeter, we have said, is always joined in parallel across the part of the circuit the voltage of which we wish to know. Now, a voltmeter has resistance, so when it is added to a part of a circuit, it reduces the resistance and increases the current. This increased current makes the voltage dropped elsewhere in the circuit somewhat bigger. Hence, the voltage apparently measured by the voltmeter is not the true value for the case when the voltmeter is removed (Fig. 28).

High Resistance

The conclusion from this is that a good voltmeter should have high resistance. Then its disturbing effect will be small, as our example above shows. A good standard is 1000 ohms per volt, but instruments are available having a resistance amounting to 20,000 ohms per volt.

CHAPTER 3

ELECTROMAGNETISM

MAGNETISM EXPLAINED. NORTH AND SOUTH POLES. LINES OF FORCE. BAR AND HORSESHOE MAGNETS. MAGNETIC INDUCTION. PERMEABILITY. MAGNETIC FLUX. FLUX DENSITY. MAGNETIC MATERIALS. COERCIVITY. MAXWELL'S CORKSCREW RULE. ELECTROMAGNET. ORDINARY ELECTRIC BELL. MOTOR EFFECT. ELECTROMAGNETIC INDUCTION. FLEMING'S RIGHT-HAND RULE.

CERTAIN substances and objects possess peculiar properties which we call magnetism. The most familiar phenomena exhibited by magnets are their ability to pick up small iron objects and their tendency, when freely suspended, to move into a north-south position as in a compass.

Magnetic Phenomena

Suppose we magnetize a knitting needle. This we can do by applying one pole of a magnet to the needle and stroking it from one end to the other, smoothly and repeatedly, always in the same direction. If we now suspend this needle by means of thread tied at the middle, we shall find that no matter how often we give it a spin it will always eventually come to rest pointing in a certain direction.

This alignment is approximately north and south. We can check this by drawing a straight line north and south (as determined by reference to a map) on a piece of paper laid on a table, and then suspending the needle over the line. Every time the needle is disturbed it comes to rest parallel to the drawn line (Fig. 1).

Let us paint one end of the needle, the one that points north, with a spot of red paint. Now swing it again and wait for it to slow down and stop. Every time, the red end points north. So we learn that there is some kind of difference between the two ends of the magnet.

The ends are called *poles*, and the one which points north is called the *north pole* of the magnet and the other end is called the *south pole* (strictly, north-*seeking* and south-*seeking*, but nobody ever uses the full terms).

This property of a magnetized needle, when freely pivoted at the middle, to point always north and south, is a very valuable one. It became known in Europe in the fifteenth century and was at once utilized on ships and permitted

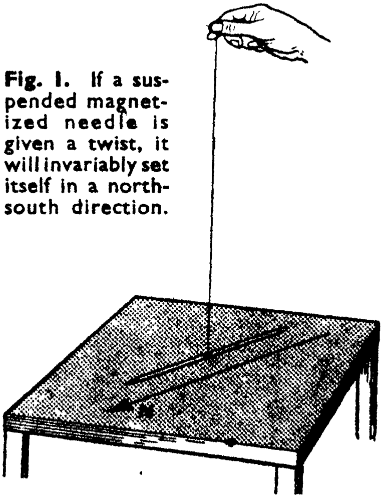


Fig. 1. If a suspended magnetized needle is given a twist, it will invariably set itself in a north-south direction.

long-distance ocean navigation to be done with some precision. The compass, as the swinging magnetic needle was soon called, is still the chief aid to navigation. One such is shown in Fig. 2.

The compass needle, bar magnet, horseshoe magnet, and the like, are known as permanent magnets, because they retain their properties for a long time and need no extra apparatus for creating the magnetism (Fig. 3).

Magnetism Defined

Scientists long searched for an explanation of this magnetism. It is now believed that some atoms and molecules are small magnets with north and south poles, due to the rotation of the electrons. A piece of material in its unmagnetized state has the directions of these minute magnets all mixed up. When the material is stroked with another magnet, the small magnets are brought into alignment, south to north, leaving "free" north and south poles at the two ends. It is then a magnet.

The materials which exhibit the phenomenon in the most marked degree are iron, steel (which is iron with an added small amount of carbon and sometimes other elements) and some of their alloys.

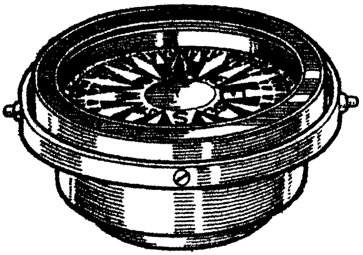


Fig. 2. One of the most useful applications of magnetism is the mariner's compass. The magnetic "needle" is fixed to the floating indicator card.

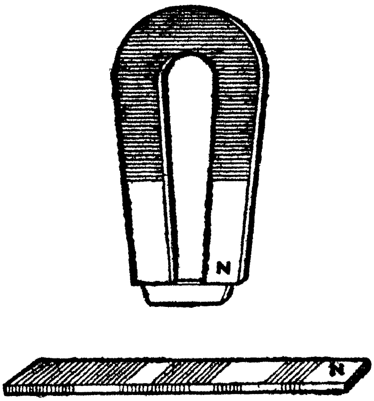


Fig. 3. Two types of permanent magnet, the horseshoe and the bar. The horseshoe has a "keeper" across its poles, which helps it to retain its magnetism.

Many materials can be made to show magnetic properties, but the energy needed to make them do so is great and the resulting magnetism so small that, as a rough practical generalization, we can say that magnets are always made of iron or an iron alloy. Because the property of iron in this respect is so outstanding, scientists have given the name *ferromagnetism* to the property.

If magnetic properties are due to alignment of molecules or atoms, we can expect that any upset of the arrangement will interfere with the magnetism. And it is so. Rough usage destroys magnetism. So does heat.

For convenience, we usually mark a permanent magnet to show the polarity, one end being marked with an N, meaning "north pole." Small compass needles, as used for experiments, usually have the north end coloured blue.

If we put on a horizontal piece

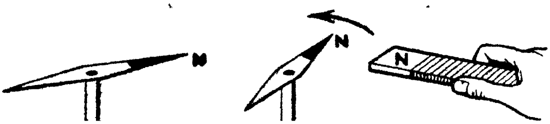


Fig. 5. Suspended compass needle at rest points to north (left), but it is repelled when approached by the north pole of a bar magnet (right).

of cardboard a small iron nail or tintack, we can control its movements by using a bar magnet underneath the card. Evidently some kind of force is acting in the space round the magnet, a force which is able to penetrate the cardboard. Again, if we put nails or iron filings on a smooth surface and slide a magnet slowly towards them, there will be a force of attraction between the two. As the distance lessens the force increases until suddenly the nails or filings leap towards the magnet (Fig. 4).

Better evidence is provided by means of a compass needle and a magnet. First, let the needle be at rest. Now approach its south pole with the north pole of the bar magnet. The pole approached swings towards the magnet.

Now let the needle come to rest after removing the disturbing magnet and then approach the needle's north pole with the same (north) pole of the magnet. This time the needle point is repelled, as shown in Fig. 5. This repulsion is the true test for the needle being a magnet. Any swinging needle of steel would be attracted by the bar magnet whatever pole of this were used. Repulsion is only exhibited when a pole of a magnet is approached by the similar pole of another magnet.

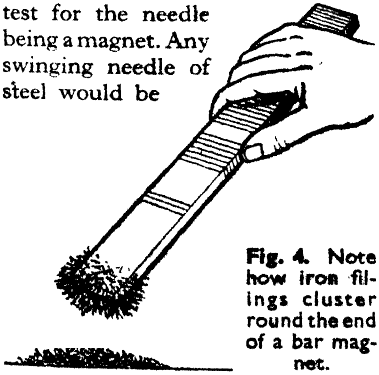


Fig. 4. Note how iron filings cluster round the end of a bar magnet.

From these simple experiments we can state a law: *like poles repel and unlike poles attract.*

Field of Force

It is evident that in the space near the magnet there is an invisible force. The region in which the force acts is called the magnetic *field of force.*

Though the field of force is invisible, we can find out something about its shape and distribution. The simplest way to do this, using a single bar magnet, is shown in Fig. 6.

A tiny compass needle is placed on a sheet of paper near the bar magnet, which is left lying in the same position on the paper all the time. When the needle is steady, mark with a pencil two points on the paper, corresponding to the two ends of the needle. Move the needle so that one end is at one pencil point and mark the position of the other end. Continue to do

needle. Draw in the needle positions with the pencil, and the result will be something like Fig. 6, where only a few positions are shown.

We see that the force operates along well-defined lines. These are called *lines of force* and, by means of the small compass needle, we can plot, or map, the lines of force for any magnetic field. In Fig. 7 lines are shown for horseshoe and bar magnets. Only a few lines are shown.

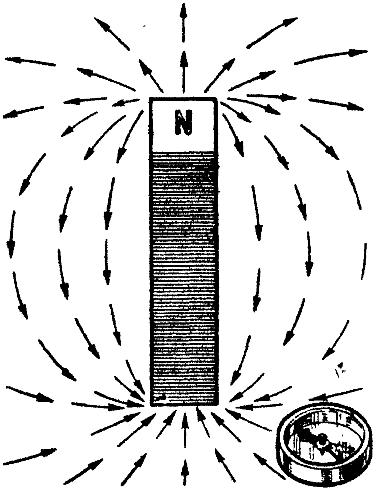


Fig. 6. Mapping the field of a magnet with the aid of a small compass. Arrows indicate the directions of the needle.

When making the experiment, we should ensure that the magnet is in its correct position north and south, for if it is a weak one the magnetic field possessed by the earth itself may distort the lines of force. Another thing to remember is that a "map" drawn in this way shows the field in one plane only, while the whole field, of course, is three-dimensional—that is, occupies a volume.

It is convenient to think of lines of force as possessing direction, and it is a convention to think that their direction and route are those which would be taken by a "free" north pole (if there could be such a thing). Lines of force "travel," that is, from north pole to south pole.

Magnetic Intensity

A horseshoe magnet has a strong "pull" near the poles. In other words, the field is there more intense than anywhere else near the magnet. In Fig. 7a is shown a section of the field for such a magnet. We notice that where the field is most intense, the lines are crowded most closely together. This fact has led to the measurement of magnetic intensity in terms of *lines*, that is, the number of lines of force passing through a square centimetre in a plane at a right angle to the direction of the lines.

Those lines of force which do not return to the magnet, represent loss of energy. If we put a bar magnet away in a drawer for a long time and then try to use it we find that it is weaker than formerly. This is because demagnetization has been going on owing to the loss of energy.

To avoid this, we try to arrange for the lines always to be closed, i.e. to begin and end on the magnet. And we achieve this by adding an extra piece of iron, a *keeper*, in the right place. One is shown in Fig. 3 and again for a pair of bar magnets in Fig. 7b.

So far reference has been made only to bar and horseshoe magnets. Often fields of special shapes and of great intensity are needed. We then shape the magnet accordingly. In Fig. 8 one arrangement is shown whereby a ring-shaped gap is produced in a permanent magnet so that a coil on a cylinder can move across the field. The lines of force traverse the gap radially, i.e. away from the centre of the centre pole, but they are omitted from the illustration in order to show the construction. Another common arrangement is shown in Fig. 9. Extra pieces of the shape required, pole pieces, are fixed to the poles of the magnet. There is another purpose in this arrangement, about which we shall learn soon.

Now why is it that a magnet attracts a piece of iron? We can satisfy ourselves that one magnet can attract or repel another magnet, but why does a magnet attract (always attract, never repel) a piece of unmagnetized iron? Let us examine the mechanism of this.

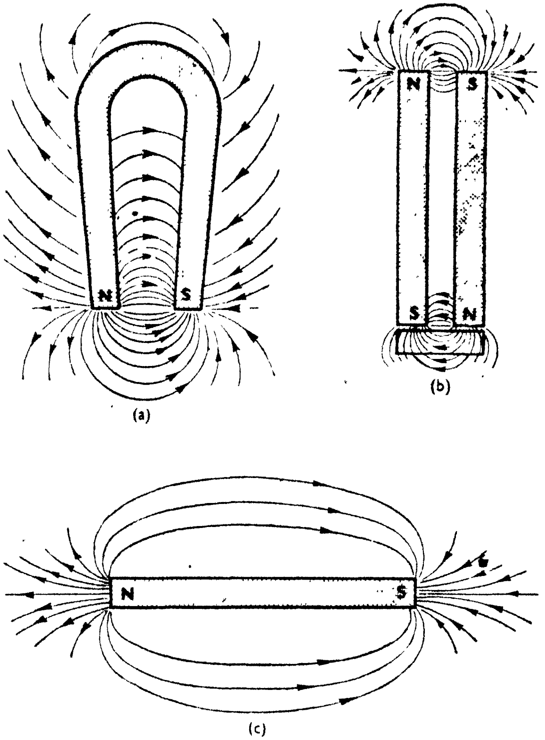


Fig. 7. (a) Lines of force round horseshoe magnet, and (b) two bar magnets placed side by side, north pole to south pole, with a keeper at one end. At (c) is seen the direction of a few of the lines of force of an ordinary bar-magnet field.

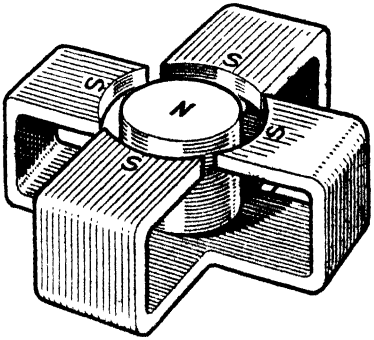


Fig. 8. Permanent magnet of the type used in some loudspeakers. Intense magnetic field exists at the circular gap.

We saw the repulsion between two north poles in the experiment illustrated in Fig. 5. Similarly, two south poles repel each other. But a north pole attracts a south pole and a south pole attracts a north pole.

Now let us put a piece of iron in the field of a bar magnet. The two states, before and after the addition of the iron, are illustrated in Fig. 10. In the second, we see that the iron has concentrated inside itself a number of the lines of force of the field of the bar magnet. We

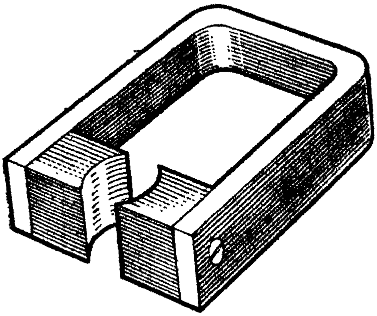


Fig. 9. Pieces of high permeability steel fitted to poles of a permanent magnet increase intensity of the field.

can check that this is correct by performing an experiment to map the field of force when the iron is added, using a small compass needle for the purpose.

We see that lines enter at the end *A* and leave the iron at the end *B*. In other words, the piece of iron corresponds to a magnet. End *A* is a south pole and end *B* is a north pole. Hence, the north pole of the bar magnet attracts the south pole of the temporary magnet. When a magnet is created in this way we say that its magnetism is *induced*, and the phenomenon is called *magnetic induction.*

We shall learn more about magnetic induction later on, but for a moment let us return over some of the ground and pick up a few further ideas and technical terms.

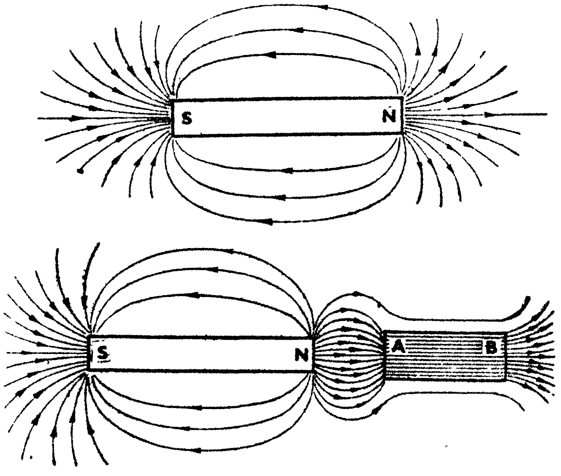


Fig. 10. Experiment showing principle of magnetic induction. Lines of force from the bar magnet concentrate in the adjacent iron and this becomes a magnet.

Reverting to the ability of a magnet to point north-south, we can now appreciate that this must be because the earth itself possesses a magnetic field. It appears that the earth acts as a large magnet with a south pole somewhere near the geographical north pole of the earth and a north magnetic pole somewhere near the geographical south pole. Any bar-shape magnet free to swing in the earth's field, therefore, aligns itself so that its north pole points to the magnetic pole near the north geographical pole. Incidentally, although we see that the pole near the north pole must be "south" in polarity, we call it the north magnetic pole.

The magnetic north is not quite at the geographical north, and the difference is called the *declination* and has to be allowed for by navigators. It varies from place to place because of distortions in the earth's field and is about 12 deg. at Greenwich, the magnetic north being that amount west of the true north. The word *meridian* is used for the line north and south, so a compass needle at rest under the influence of the earth's field is said to be lying in the meridian.

Permeability

In Fig. 10, we see that many lines have been concentrated inside the iron, more than would have been in the same area with the iron absent. The measurement of the ability of a substance to effect this concentration is called *permeability* (symbol μ, the Greek letter "mu"). A substance of high permeability captures more lines by induction than does a material of low permeability.

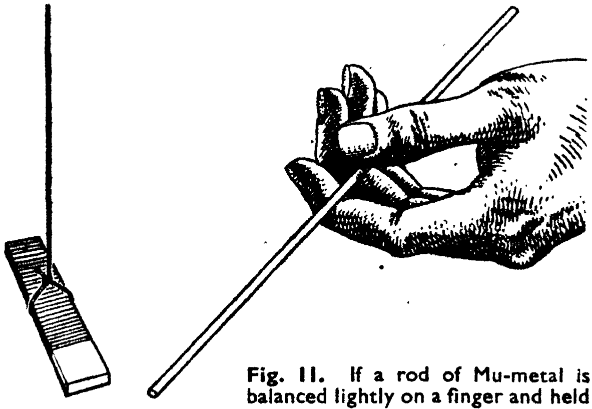


Fig. 11. If a rod of Mu-metal is balanced lightly on a finger and held in line with the earth's magnetic field it becomes a temporary magnet. This may be tested by bringing a north pole of another magnet near the north pole of the temporary magnet, when repulsion is seen.

Permeability is measured as the ratio of the number of lines in the material to the number of lines in the same area in air. So for air, $\mu = 1$, and is the same value for all non-magnetic materials.

It is interesting to repeat the experiment of Fig. 10, but using a flat ring of iron instead of a straight bar. We find that in the space inside the ring there is no field at all. This means that we can screen a space from the effects of a magnetic field by enclosing it in a magnetic material. This is called *magnetic screening*. For example, if a watch is enclosed in a steel case, the delicate works and the steel spring cannot be upset by any magnetic field in which the watch is likely to be subsequently placed.

There is a limit beyond which we cannot magnetize a piece of iron or steel. Once we have reached the stage where all the molecular or atomic magnets are aligned, no further applied magnetizing force of any size whatever can affect the specimen. What is known as *magnetic saturation* has been reached.

The total amount of magnetism available to affect any other magnet or magnetic material is called the *magnetic flux*, represented by the symbol Φ (Greek capital letter "phi"), and measured in *maxwells*, though engineers usually prefer to use the expression "lines." We may have a bar magnet from the end of which come 1000 maxwells or lines. This is the flux.

Flux Density

The force available depends on the concentration of the lines. For example, if the bar magnet mentioned has a cross-sectional area of

10 square centimetres, it is less powerful, so to speak, than if the area were 2 square centimetres. So to get a measure of the force, we divide the total flux by the area through which it passes, and this is known as the *flux density* or *induction*, represented by the symbol B, and measured in units called *gauss*, one gauss being equivalent to one maxwell per square centimetre.

The greater the permeability of a substance, the more lines will it concentrate into itself from a magnetic field. And it has been found that certain alloys have high permeability and so are very suitable for pole pieces, because they concentrate a strong field in a comparatively small space.

Special Alloys

Alloys possessing exceedingly high permeability in weak fields are now marketed under various names. The earliest, an iron-nickel alloy, was called Permalloy, and later ones, improved by the addition of extra elements, are Perminvar, Hypernik and Mu-metal. These are trade names, but one or two have become so familiar that we refer to them as if they were general ones.

Magnetized by Induction

The permeability of these is so high that they can become magnets by induction when resting in the earth's magnetic field. This can be demonstrated with a thin rod of Mu-metal. If it is held balanced at the middle on a finger and pointing to the magnetic north, it can be shown to be a magnet by approaching it with a magnet and so getting repulsion, or by approaching it with an unmagnetized knitting needle, when attraction results. If the piece of Mu-metal is turned out of the magnetic meridian, the attraction disappears (Fig. 11).

Sometimes we need a material which will retain its magnetism under conditions which might demagnetize an ordinary iron magnet. Such a material will be difficult to magnetize because of this, and is said to have high *coercivity*. The best of all these is cobalt steel, and this is used, or a trade variant, with improved qualities, for

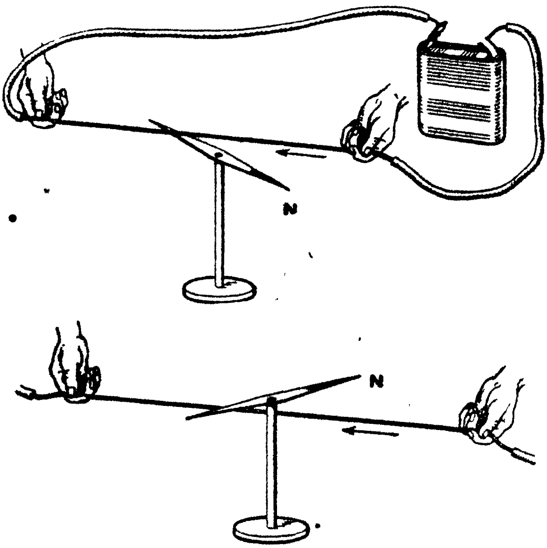


Fig. 12. It can be demonstrated that magnetism and current are associated if a current-carrying wire is held first above a magnetic needle at rest and then below it: the needle moves in the directions shown.

permanent magnets after the style shown in Fig. 8, designed for permanent-magnet loudspeakers.

When a magnet is made to pass through a cycle of magnetizing changes, energy is lost owing to *hysteresis*, the nature of which is too complicated for explanation here. So manufacturers aim at producing alloys which shall have low hysteresis losses. That is why the very permeable alloys already mentioned have been improved by the addition of other elements than nickel to the iron.

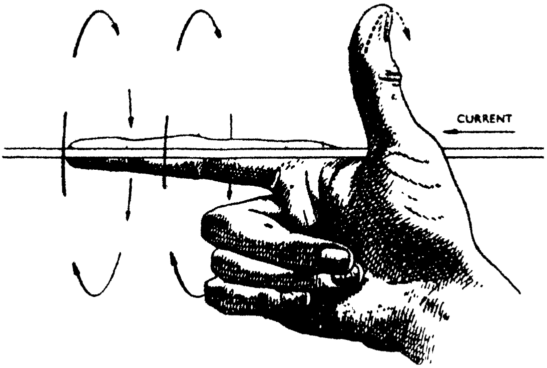


Fig. 13. Maxwell's Corkscrew Rule states the direction of the lines of force around a straight conductor. By pointing the forefinger in the direction of polarity, extending the thumb, and turning the hand as if driving a corkscrew, the thumb will indicate the direction of the lines of force.

Proved Relationship

So far we have considered magnetism as a force on its own, unconnected with electricity. Mention of the fact that it is a property exhibited by some atoms and molecules will have suggested that it has some association with the electron and, therefore, with electric current. This is indeed the case, although the relationship was not discovered until just over a hundred years ago.

A simple experiment demonstrates how magnetism and current are associated. Current is passed through a conductor which is held near a magnetic needle, and it is seen that the needle is deflected. As the conductor is not made of magnetic material, the deflection must be due solely to the electric current. This is verified by breaking the circuit, when the current stops and the needle returns to its position of rest in the meridian.

If we perform the experiment with a little care, we can detect the configuration of the magnetic field of force which results from the current. The arrangement is illustrated in Fig. 12.

First the wire is held parallel with the needle and above it. The north pole of the needle is deflected in one direction. Then the wire is held underneath and the north pole is deflected the opposite way. This shows us that the lines of force are going round the conductor. In fact, they form concentric circles round each part of the wire.

Corkscrew Rule

The direction of the lines of force round a conductor is stated in easily memorized form in Maxwell's *Corkscrew Rule*. Point the forefinger in the direction of polarity (from positive to negative) and turn the hand as if driving in a corkscrew, the thumb being extended. The thumb then traces

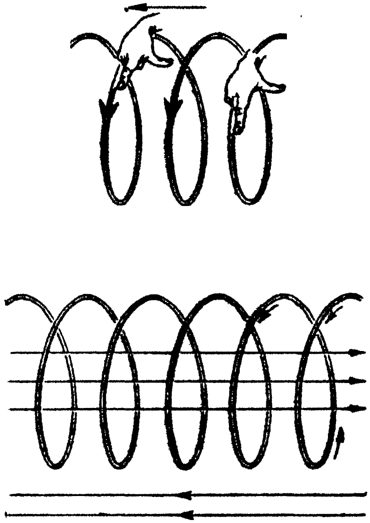


Fig. 14. Maxwell's rule applied to a wire wound in the form of a coil.

out the direction of the lines of force, as shown in Fig. 13.

The field can be concentrated by winding the conductor into a coil. This is suggested in the upper part of Fig. 14, the thick parts indicating the front of the coil. If we could perform the acrobatic feat of following the current with the right hand, turning it all the time as for the experiment of Fig. 13, we should find that the lines of force align themselves as suggested in the bottom part of Fig. 14.

If we refer back to Fig. 7c, we see that the lines of force of Fig. 14 are very similar to those of a bar magnet, taking into account the omission of the lines through the magnet in Fig. 7c.

In fact, a coil with current flowing through it is for the time being a magnet, with a north pole at one end and a south pole at the other end. It is an *electromagnet.*

Intensifying the Field

If a magnetic material is placed inside a coil, thus making a core, the magnetic field is concentrated still further and so made more intense. We can verify this, if we wind a coil and pass current through it, bring one end near a magnetic needle and then introduce an iron core and watch the violent effect on this needle. The greater the permeability of the core, the stronger will be the flux.

An elementary electromagnet can be made by winding some insulated wire on an iron nail and connecting up a battery as shown in Fig. 15. It will pick up small iron or steel objects, show polarity by repulsion on another magnet free to rotate, and show a field of force just like that of a bar magnet.

There is a simple rule for finding the polarity of an electromagnet. We look at an end of the coil. If

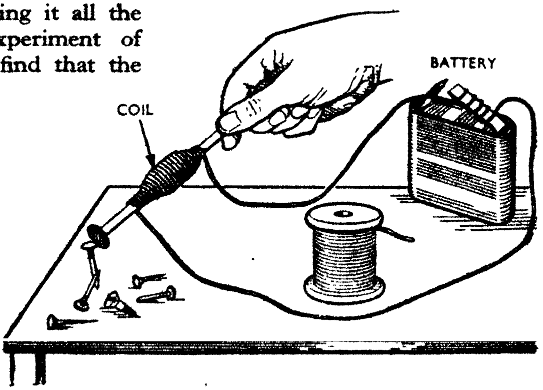
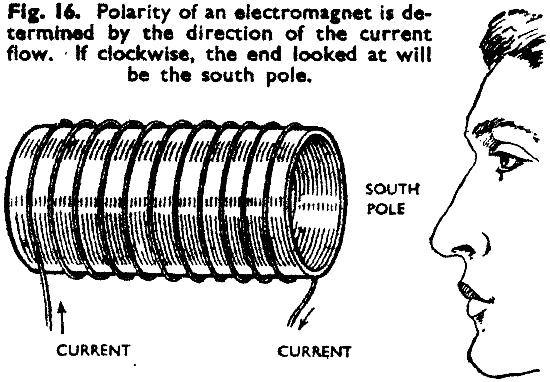


Fig. 15. An iron nail becomes a magnet when current passes through a coil of wire wound round it.

the current is flowing clockwise, the end looked at is a south pole. We must find the current direction, of course, by noting the connections to the battery supplying the electricity. If the end looked at has the current flowing in an anti-clockwise direction, then this end is a north pole. Fig. 16 illustrates these rules.

Fig. 16. Polarity of an electromagnet is determined by the direction of the current flow. If clockwise, the end looked at will be the south pole.



Electromagnets can be made in a variety of shapes. For example, if we wish to have an electromagnet similar to the horseshoe magnet in its concentration of field near the two poles, we can wind two coils on a bent iron core, one coil on each limb (Fig. 17).

The winding must be such that the current direction produces a south pole at one end and a north pole at the other. This is achieved, if the conductor making the two coils is continuous, by winding the two coils in opposite directions.

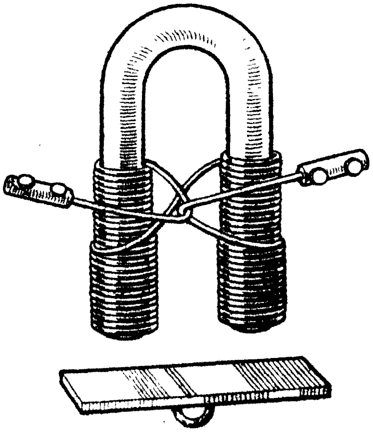


Fig. 17. An electromagnet magnetically equivalent to a permanent magnet of the horseshoe type illustrated in Fig. 7.

Electromagnets can be made more powerful than permanent magnets, generally speaking, and have the advantage of being magnets only when required, for the effect ceases when there is no current. They have many uses in everyday life and in industry. Immense electromagnets may be used to act as holders on cranes, and so pull up tons of scrap metal which would have to be loaded into containers to be lifted by cranes in the normal way. Carefully made electromagnets are used in very many instruments, and in the "energized" loudspeakers employed in radio receivers.

Electric Bell

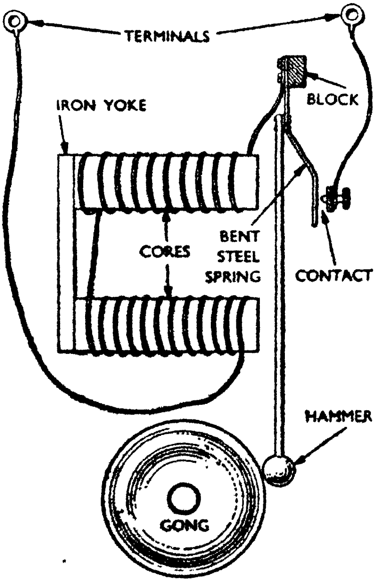
The commonest application of the electromagnet is seen in the ordinary electric bell (Fig. 18). Coils are wound on two iron cores fixed to an iron yoke, the direction of winding being such as to make one core have a free north pole, and the other core have a free south pole. One end of the winding is

other end of the winding goes to a steel spring shaped as in the diagram. The end of the spring at which the wire is joined is fastened to a block on the baseboard and the other end is bolted to an iron bar which terminates in a rod carrying the bell striker. The iron bar is parallel to the pole faces of what is seen to be a U-shape electromagnet.

The spring touches the point of a small screw (the point is often coated with a non-corrodible hard metal) held in position by a threaded collar fixed to the baseboard. From this screw a wire goes to the second terminal.

The action is easy to understand. The terminals are joined through a switch to a battery. When the switch is closed, current flows through the windings and makes the cores into electromagnets.

The iron bar becomes magnetized by induction, is attracted and moves towards the poles. As it does so it pulls the spring away from the screw point and breaks the circuit. The current stops, the cores cease to be electromagnets and the spring returns the iron bar to its original position. This brings the spring once more into contact with the screw point, the circuit is completed and the whole cycle is started again. All the time the battery is connected the bar or *armature* is vibrating backwards and forwards and the knob is hitting the gong.



[illegible] Circuit diagram of an ordinary electric bell. Note the electromagnet.

This interrupter action has been explained in some detail because it is utilized in a number of devices, including the induction coil and the vibrator used for creating high-tension voltage from the battery of a motor-car. If the bell gong is removed, the bell becomes a buzzer. Small buzzers are made with but one electromagnet, the two being needed in a bell because of the length of the rod to be moved (Fig. 19).

Ampere-turns

The strength of an electromagnet is directly proportional to both the amperes flowing and to the number of turns on the coil or, as we say, to the *ampere-turns*. One ampere through ten turns will produce the same magnetizing force as two amperes through five turns—in each case the strength is 10 ampere-turns.

The magnetizing force (field strength) produced is given the symbol H. If the core is air, then this magnetizing force is equal to the flux density, there being nothing present to interfere. But if there is a core with any permeability greater than 1 (the permeability of air), then the induction or flux

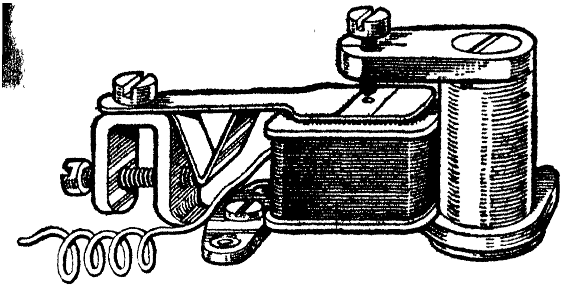


Fig. 19. Buzzers operate on the same principle as electric bells, except that they have no gongs.

density is greater in proportion. This is expressed in the equation $B = \mu H$.

For example, if the current in the coil produces 10 lines of force per square centimetre of cross-sectional area, then, if there is no core of magnetic material, the flux density is also 10 lines per square centimetre, i.e. 10 gauss. But if a material of permeability 1000 is introduced, then this concentrates a thousand times more lines per square centimetre. In other words, the flux density is now 10,000 gauss.

We can see now why we need materials of high permeability for the cores of electromagnets. Of course, the use of a core does not give us "something for nothing" –what it does is simply to concentrate the lines of force in a smaller space, so that instead of a large and relatively weak field we get a small and intense one.

Already we have seen that there is a force acting between permanent magnets, the force which produces attraction and repulsion.

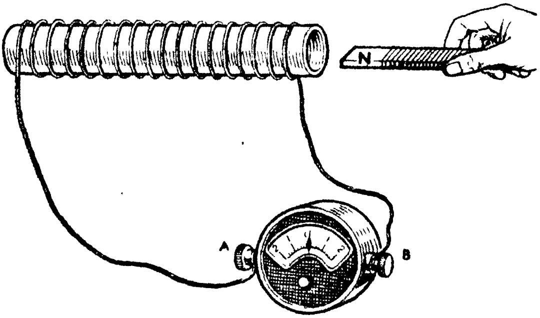


Fig. 20. This simple experiment demonstrates one of the most important of all the principles encountered in electrical engineering. This is electromagnetic induction by which the movement of a magnetic field causes the flow of an electrical current.

In the same way, a force is set up between a magnet and a conductor carrying a current, because the latter is creating a magnetic field as well.

Which of the two moves under the force, the conductor or the magnet, depends on which is free to do so. For example, two light coils mounted on a spindle and free to rotate will both move when current is passed through them, because both become magnets. In the case of the electric bell, the induced magnet, the iron rod, moves, because it is free to do so, while the electromagnet is fixed.

In general, we may say that any device in which motion results from the passage of electric current is an electric motor. This motion is the ***motor effect.*** As we shall see in later chapters, it is the basis of electric motors and also of most measuring instruments.

If magnetism can be created by means of an electric current, is the

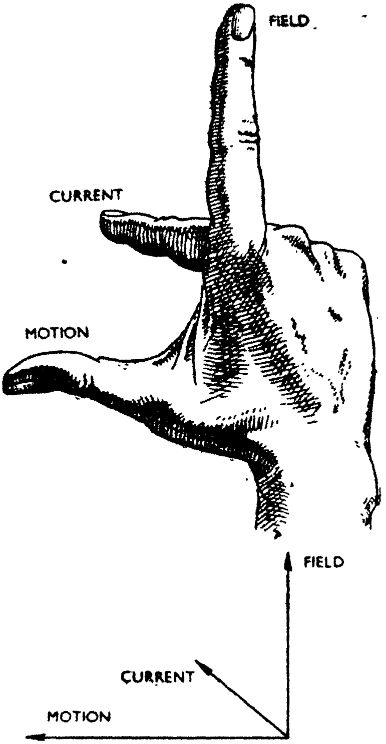


Fig. 21. Fleming's Right-hand Rule. The lower diagram shows the three directions mutually at right angles.

reverse possible? Can we create electricity from magnetism?

A simple experiment demonstrates that we can. A long coil is wound on a cardboard cylinder, and the ends of the winding are taken to a current-indicating instrument with its zero in the centre of the scale.

A bar magnet is held in the hand and plunged into the coil at one end. We observe a "kick" on the instrument; that is, the pointer suddenly swings over to the one side of the scale. Now we leave the magnet at rest inside the coil. The instrument needle returns to zero. The magnet is next quickly withdrawn from the coil. Again a kick is registered, this time in the opposite direction to the one observed before. Then the needle returns to rest. This experiment is illustrated in Fig. 20.

So we see that when the magnet is plunged into the coil, then a current flows, but only while the magnet is moving. The withdrawal shows us that the direction of the current is related to the direction of motion of the magnet. We have, in fact, created an electric current by moving a magnetic field near a conductor.

The e.m.f. produced in the coil is said to be *induced*, and the phenomenon is called *electromagnetic induction*. More commonly, we say that the e.m.f. is *generated*. This discovery was made by Faraday, probably the most important of all his many discoveries.

Drifting Electrons

Protruding from the poles of the magnet used in this experiment are invisible lines of force, spreading out as already shown. As the magnet is plunged into the coil, these lines of force are "cut" by the conductors forming the turns. This cutting creates the e.m.f. The effect of suddenly subjecting the conductor to a magnetic field is enough to set some of the free electrons drifting along in one direction.

This direction is such that it tends to set up a magnetic field in opposition to the one already being used to upset the neutral condition of the conductor. In the apparatus of Fig. 20, the current, therefore, flows through the wire so as to enter the instrument at *A* and leave it at *B*, thus making the end opposite the magnet a north pole.

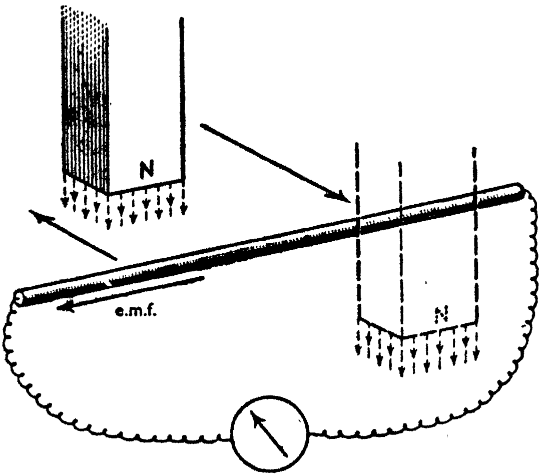


Fig. 22. Direction of e.m.f. is the same whether the magnet moves from left to right, or the conductor from right to left under the magnet pole.

In order to arrive at the direction of the current flowing when generated in this way, we use a rule.

The rule is Fleming's *Right-hand Rule*, by means of which we can find out the direction of current flowing in any conductor when it is made to cut the lines of force of a magnetic field. It is illustrated in Fig. 21. The thumb, first finger and second finger of the right hand are extended mutually at right angles. If the thumb indicates the direction of motion of the conductor relative to the field, and if the first finger points in the direction of the field, then the second finger points in the direction of the e.m.f. generated or induced.

We have spoken of "cutting" the lines of force, because this is the word most used by electrical engineers when discussing generation. Actually, the essential condition is *change* of the magnetic flux near a conductor, and so sometimes we hear of the expression *linkage* instead of "cutting the lines of force," any change of the linkage of flux with a conductor being effective in inducing an e.m.f.

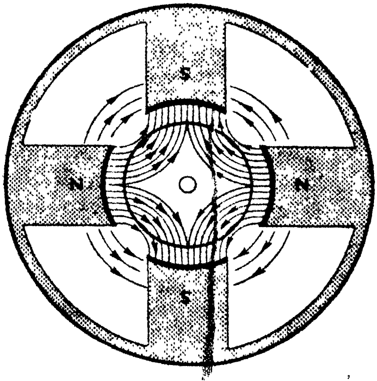


Fig. 23. Showing how the lines of force are concentrated in the magnetic system of an electrical generator.

We can get a general idea of the size of e.m.f. generated by varying the experiment of Fig. 20. First move the magnet into the coil slowly and note the size of kick on the instrument. Then repeat, after the magnet has been removed, with the magnet moved more quickly. The kick registered is bigger. So the size of the e.m.f. depends on the speed at which the lines of force are cut, increasing with the speed. Now use a more powerful bar magnet and repeat the experiment, and we find that the e.m.f. is again bigger.

These facts can be summed up

by saying: the size of the e.m.f. generated is directly proportional to the number of lines being cut per second. This applies to each separate conductor. To get the answer in volts we divide the number of lines cut per second by 100,000,000, expressed more neatly as 10^8.

In many generators, the magnetic system remains stationary and the conductors move. But, obviously, the principle is the same (Fig. 22). There is, however, the very great difference that in an electrical generator hundreds of conductors cut millions of lines, perhaps as fast as twenty times a second. We can see how necessary it is to have pole pieces of the correct shape and quality to ensure that the greatest possible number of lines is cut and not wasted in the outer space (Fig. 23).

All this has been based on the experiment of Fig. 20. Faraday's original experiment was done with apparatus like that shown in Fig. 24. Not only was the fact of electromagnetic induction established, but there was yet another result as well. This result is also very important. It was found that a kick was obtained on the instrument of coil *B* when the circuit of coil *A* was made or broken. This we should expect. Also it was found that if the number of turns on *B* was altered, then the kick was changed in size, though *A* remained the same.

Turns Ratio

We can understand this. For when the circuit of *A* is made, then the iron ring becomes a magnet and its flux is suddenly associated with coil *B*. And the size of the e.m.f. generated in *B* is proportional to the number of turns in this coil, as we have already seen in the calculation above.

The consequence of this is that if we have double the number of turns in *B* compared with *A*, then the e.m.f. across *B* is twice that suddenly created across *A*. So we can *transform* an e.m f. from one value to any other we wish, *as long as it is changing*. That is very important. There is no effect in *B* while current is flowing steadily through *A*, because there is no magnetic cutting or change in linkage.

We call this the *transformer effect*. If we wind two coils on a magnetic core, i.e. iron or iron alloy, then, if the turns in one coil are, say, 50, call this coil *X*, and if the turns in the other coil are, say, 500, call this coil *Y*, we have a device called a *transformer*.

If 20 V are suddenly created across

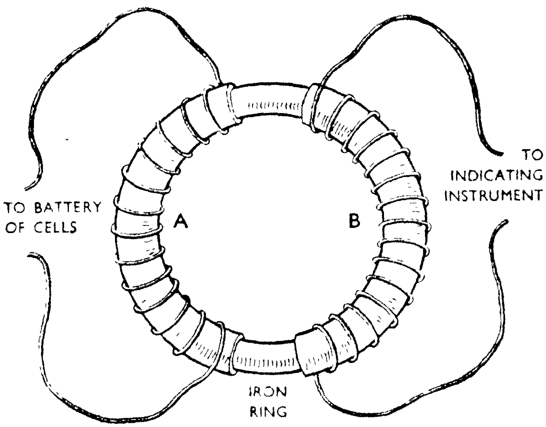


Fig. 24. Simple circuit for an experiment which clearly demonstrates the transformer principle.

X, the voltage across *Y* will be 200. Or if 200 V are suddenly created across *Y*, then the voltage across *X* will be 20. So we can use the transformer to step up or step down, just as we wish. The coil through which the energizing current is made to flow is called the *primary* winding, and the one through which the current is induced is called the *secondary* winding

Needless to say, a transformer does not give us something for nothing. If we get a step-up of voltage we pay for it in the shape of a reduction in current. A step-down of voltage is attended by a step-up of current. We get only as much power out of the secondary as is put into the primary—in fact, slightly less, because there are losses in the copper and iron of the transformer.

A transformer can be used only if there is change of flux. A steady current produces no transformer effect. A supply which is changing in size and direction all the time can, however, be transformed. In other words, we need alternating current, or A.C., if we wish to use a transformer.

Use of Transformers

Transformers are now used very extensively on A.C. circuits. We can distribute 132,000 V over high-tension cables to transformer stations, there change it to 11,000 V, and distribute this supply through the country to transformers which change it to 230 V for domestic use.

There is one way in which we can utilize the transformer effect with ordinary D.C. supplies such as from a battery or D.C. mains. This is by the use of the trembler interrupter action as used in the electric bell. This automatic switch is placed in the primary circuit, and the continual making and breaking induces e.m.f.'s in the secondary proportional to the turns ratio. Such an arrangement is called an *induction coil.*

A large induction coil can be wound with such wire and such a ratio of turns that a primary supply of 24 volts can be made into a secondary e.m.f. of as much as a quarter of a million volts. Such a voltage will cause a spark of some ten inches in air.

Self-induction

Electromagnetic induction applies even in a single coil. If we have a coil, and switch on a supply from a battery, the coil becomes an electromagnet. As the field spreads outward from each turn it cuts the neighbouring turns and induces an e.m.f. in them.

The direction of this e.m.f. is, as usual, such as to oppose the change, and so is known often as a "back e.m.f." Its size depends on the number of lines cut per second by the conductors, and so the quicker the build-up or decay of the current, the greater is the back e.m.f.

This inductive back e.m.f. may be of great size, and in heavy circuits employing quick-action switches and containing coils we have to install protective gear to safeguard apparatus from high "surge" e.m.f. at make and break.

The phenomenon is known as *self-induction* and the property it gives to coils we call *inductance.* The phenomenon is so important that we must have some means of measuring it in order to be able to do calculations on A.C. circuits. The unit used is the *henry* (H). A coil has inductance of one henry when a change of one ampere per second causes a back e.m.f. of one volt.

We usually think of coils in connection with inductance. In fact, however, every conductor has some inductance, because a magnetic field is created near it. But the effect is so small in a conductor not in the form of a coil that we can usually ignore it. We cannot do so, however, when dealing with A.C. supplies varying millions of times per second, such as the e.m.f.'s we get in radio work.

Retarding Effect

Inductance can be thought of as the electrical equivalent of inertia. Inertia opposes the acceleration of a body—except for inertia, a motor-car, for instance, would start travelling full out as soon as the clutch was engaged. In the same way, it is inductance which prevents a current obtaining its maximum size instantaneously.

Magnetomotive Force

We have stated that the magnetizing force H is directly proportional to the ampere-turns. By using this and one or two other facts, we can develop a method of calculating electromagnetic effects analogous to the Ohm's Law of electrical circuits. We then use the expression "magnetic circuit."

The whole circuit is the core, and may be continuous as in Fig. 23, or have gaps or be but part of a circuit as in the case of a straight electromagnet.

We may call the magnetizing force the *magnetomotive force* (m.m.f.). This, in gilberts, is calculated from the ampere-turns as follows: m.m.f. $= 0{\cdot}4\pi NI$, where I is amperes and N number of turns. The gilbert is the unit of m.m.f. to produce a flux density of one gauss in a coil of unit dimensions.

We realize there must be a difference in the strength of flux according to the length of core over which the m.m.f. operates. So the field H is obtained per centimetre length of magnetic circuit by dividing the m.m.f. by the length.

The flux density is equal to μ times H. The total flux is equal to the flux density multiplied by the cross-sectional area of core. This flux may be considered as analogous to electric current.

So if A is the cross-sectional area, μ is the permeability, l is the length of path, H the field intensity in air, and Φ the flux, we have:

$$\Phi = \mu A \times H.$$

But H is equal to the m.m.f. divided by l. So we can write:

$$\Phi = \frac{\mu A}{l} \times \text{m.m.f.}$$

If the flux is analogous to current, and m.m.f. is analogous to e.m.f., we can call the rest by a special name which will give us the magnetic equivalent of Ohm's Law. Let us rewrite the above equation:

$$\text{m.m.f.} = \text{Flux} \times \frac{l}{\mu A}.$$

Calling the part on the end of the right-hand side, the *reluctance*:

$$\text{m.m.f.} = \text{Flux} \times \text{Reluctance},$$

which is analogous to,

$$\text{e.m.f.} = \text{Current} \times \text{Resistance}.$$

The above equation is the basis of magnetic circuit calculations.

These calculations are obviously not applied as extensively as calculations relating to electrical pressures and currents, but they are of supreme importance in the design of electric motors, generators, transformers and various other articles of electrical equipment.

CHAPTER 4

GENERATION OF ELECTRICITY

EDDY CURRENTS. GENERATOR ACTION. COLLECTING BRUSHES. ROTATION OF LOOP. ALTERNATING CURRENT. COMMUTATOR. DIRECT CURRENT. TWO-POLE MAGNETIC SYSTEM. COMMERCIAL FOUR-POLE MACHINE. EXCITATION. FIELD COIL AMPERE-TURNS. MAGNETIC LEAKAGE. ARMATURE COILS. EFFICIENCY OF GENERATION. TEMPERATURE RISE. LOSSES. OUTPUT LIMITATIONS.

BEFORE describing how conductors are made to move in generators, there is one other aspect of electromagnetic induction to take into account, as it has some bearing upon later matters; it is the production of e.m.f.'s and currents in conductors other than straight bars or wires.

Current Flow

For instance, if a magnetic pole be moved over the surface of a sheet of metal, say copper or iron, the lines of force of the magnet will take some path through the sheet, and we have the relative movement of magnetic field and a conductor, in this case the iron or copper. This must result in the generation of e.m.f.'s, but what will be their direction and where will the current flow?

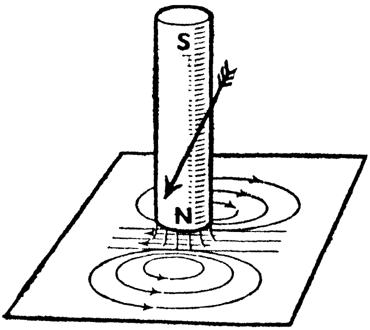


Fig. 1. Movement of a magnet over a sheet of metal causes eddy currents. Here the direction is towards the reader.

Fig. 1 will help us find the answers. The diagram can be followed if we consider the surface of the metal sheet to be made up of strips of metal; what are known as "eddy," or Foucault, currents will flow in circles in the sheet, generally as indicated in Fig. 2. In practice these eddy currents can be a great nuisance.

Opposing Force

Before getting back to practical generators, there is one obvious but important thing to mention. When a current is produced by moving a magnet or wire, we do not get that current for nothing. We have to work for it. What happens is that the induced current itself sends out lines of force and these oppose the passage of those which induce the current. Therefore, it is harder to push a magnet into a [illegible] than a plain bar

The bigger the current set up, the more work would have to be done in pushing the magnet. In large generators some thousands of horse-power is needed to move the conductors in the magnetic field.

Loop Conductor

Let us now continue with the simple form of magnetic field seen arranged horizontally in Fig. 3. In the gap between the poles we see a simple loop conductor arranged so that it rotates upon a central shaft. Obviously, the connections from this loop to the meter, and to what will later be the external circuit, cannot be fixed or, during

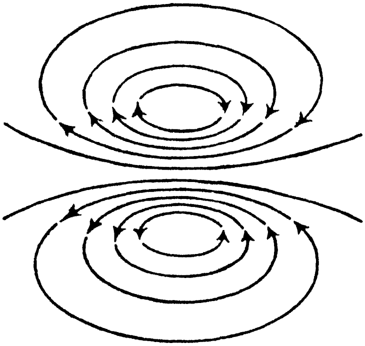
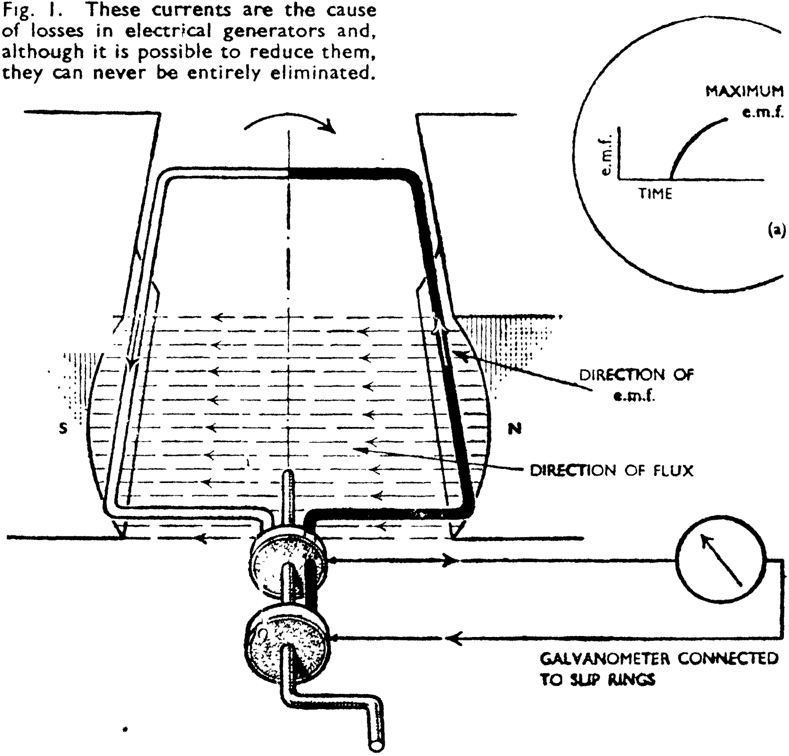
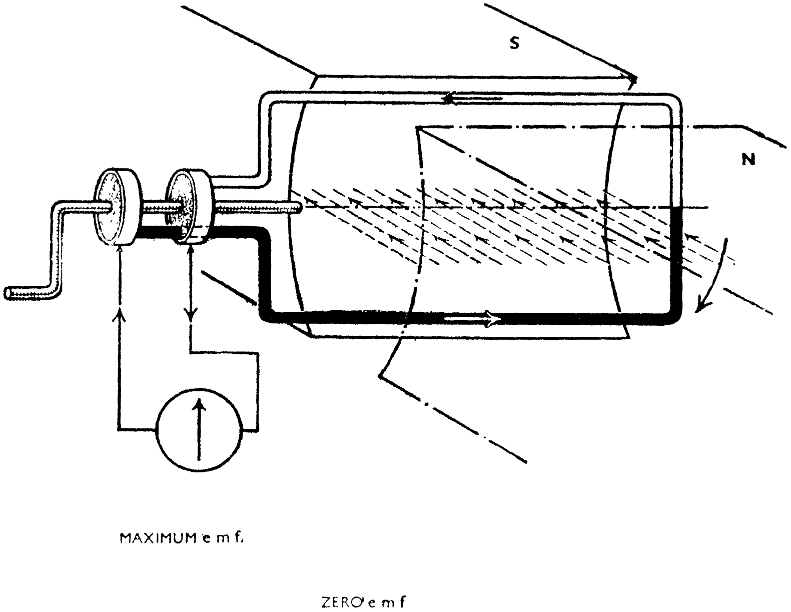


Fig. 2. Direction of eddy currents set up in the sheet of metal illustrated in Fig. 1. These currents are the cause of losses in electrical generators and, although it is possible to reduce them, they can never be entirely eliminated.



SIMPLE FORM OF GENERATOR

Fig. 3. As the loop conductor is rotated between the poles, it cuts the lines of force existing between the magnetic poles, and an e.m.f. is generated as shown at (a), top right-hand corner of the illustration. Owing to the difference in the rate of cutting the lines, the increase of e.m.f. does not follow a straight line.



TURNING LOOP THROUGH FURTHER 90 DEG.

Fig. 4. Magnitude of e.m.f. is shown as falling from maximum to zero in the form of a curve. Although speed of rotation is constant, the rate of cutting varies with the angle at which the conductor meets the lines of force.

the rotation of the loop, they will become hopelessly twisted and eventually dragged off.

The loop is terminated, therefore, by two rings, insulated from one another and from the central shaft. Collecting "brushes" press upon these rings so as to convey the current flowing in the loop to the external circuit or meter.

Rotating Movement

A handle is indicated at the end of the shaft to help us visualize the loop conductor being rotated in the magnetic field, but for the sake of clarity the bearings in which the shaft would turn have been omitted.

It will be noted that the faces of the magnetic poles have been shaped the better to accommodate the rotating loop. This feature will be seen also in all practical and standard generators.

Generation of e.m.f.

Let us imagine we are commencing the rotation of the loop in a clockwise direction. For easy reference, half the loop is shown black and we will assume this part is at the top at starting. A slight movement of the handle to and fro will generate no e.m.f. because the loop is not cutting the lines of force but merely sliding along them, as it were.

By making a quarter turn of the loop, however, and bringing the black portion immediately opposite the *N* magnetic pole, lines of force will be cut and an e.m.f. generated.

Even so, the cutting of the magnetic lines has not been carried out at a uniform rate. It is slow at first—as the loop is still more or less sliding along the lines instead of cutting them—but the rate of cutting increases as the conductor approaches the centre of the magnetic pole.

Rising e.m.f.

As we watch the meter we shall see that the generated e.m.f. rises from zero to some point of maximum value more or less very gradually.

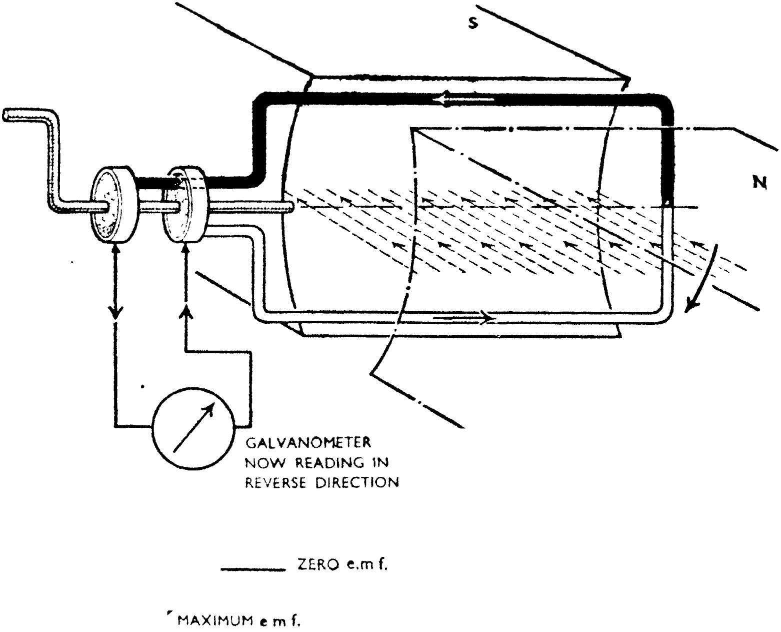
We can get a drawing of the way the voltage (or current) rises if we mark out a horizontal line to represent the position of the loop from time to time and then set out above this a number of points representing the strength of the voltage (or current) at these positions.

Joining up the dots gives a curve like that in Fig. 3a.

Two Moving Conductors

Before proceeding further with the rotation of our loop, we had better clear up a complication. We now have *two* conductors moving in the same magnetic field, one opposite one pole and one opposite the other—and they together form one conductor.

Luckily everything works out happily. The application of Fleming's Right-hand Rule to the loop shows that while the direction of e.m.f. and current in the black



REVERSED DIRECTION OF CURRENT FLOW

Fig. 5. During the second half-turn the black portion of the loop conductor moves upwards and the e.m.f. which is generated is in the opposite direction.

portion of the loop is *away from* the handle, in the light portion it is *towards* the handle. The e.m.f.'s and currents in the two halves are complementary and add together.

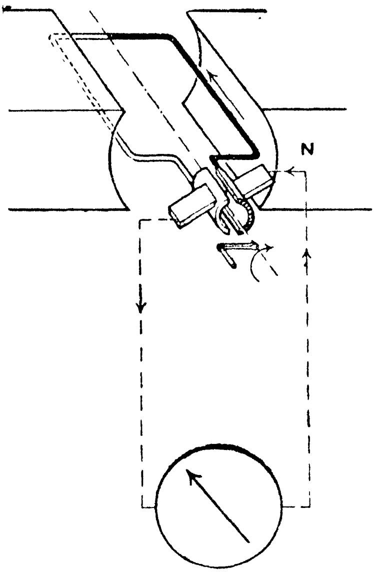


Fig. 7. By introducing a commutator, the connections from the loop conductor are reversed at just the right moment to keep the current in the external circuit flowing unidirectionally

Meter Readings

If the rotation of the loop is now continued through a further 90 deg. the meter pointer starts off at a maximum reading. As the loop approaches the vertical, however, with the black portion downwards, the meter indicates that the e.m.f. is dying down.

This is explained by the fact that the *rate* at which the magnetic lines are cut is changing, but in the reverse way to that experienced during the first quarter turn.

Falling e.m.f.

The falling e.m.f. is shown graphically in Fig. 4 with the present position of the loop and its operating handle.

It is hardly necessary to consider the remainder of the revolution by quarter turns, and we will make one bold half-turn to bring the loop back to its original position. Fleming's Rule tells us that the e.m.f. resulting from this movement is in the reverse direction, for although the direction of the magnetic lines is unchanged, yet the direction of movement is reversed and is upwards for the black portion instead of in a downwards direction.

The magnitude of the induced e.m.f. can be shown graphically, as before, but it will be placed on the opposite side of the zero line. Fig. 5 indicates the position of the loop, and also the e.m.f. generated during the second half-turn.

The magnitude and direction of the e.m.f. during a whole revolution of the loop can now be built up into a continuous line, as in Fig. 6. From this it will be seen that in rotating through the first 90 deg. the e.m.f. was built up from zero to maximum. Through the next 90 deg., from

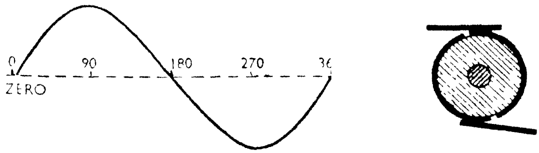


Fig. 6. The e.m.f. or current generated in the loop during a full 360 deg. rotation, is first in one direction and then reverses as indicated by above "curve." A commutator (right) is used to secure a unidirectional output from the generator.

90 to 180, the e.m.f. fell away from maximum to zero. In passing from 180 deg. to 270 deg., it again built up to maximum, but in the reverse direction. From 270 to 360 deg. this maximum again declined to zero.

In Fig. 6, therefore, we have a pictorial representation of the e.m.f. or current produced during one revolution of a simple loop conductor. This diagram — or rather the current it represents—is very interesting and important.

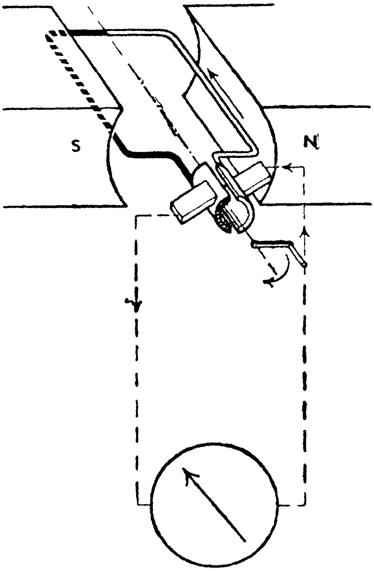


Fig. 8. Although the loop has passed through 180 deg., the segments have changed round under the brushes.

For one thing, it is a current which reverses periodically, a thing that battery currents, with which we are more familiar, *never* do. It is, therefore, called an "alternating" current, and what we see in Fig. 6 is one alternation, or "cycle."

The special characteristics of this current are dealt with in a later chapter, but it is clear that if we wish to produce a direct current from this generator—meaning a current which flows in the same direction all the time, as does a battery current—then we have to provide some means for reversing the e.m.f. at the 180-deg. point of the revolution of the loop.

Commutation

What we have to do is devise a method of connecting the external circuit to the rotating loop so that, although the e.m.f. and current still reverse in the loop, yet, as regards the external circuit, the current is in one direction only. This method is found in a device called a commutator, which "commutes" the direction of the current at the correct moment: it consists of a split ring of metal as indicated in Fig. 7. In practice, these commutator segments are mounted on insulating material.

In Fig. 7 the loop is shown connected to the commutator, and it has been rotated from the vertical through 90 deg. so that the black portion of the loop is now opposite the *N* pole. As before, the e.m.f. and current direction is *away* from the driving handle in the black conductor, and *towards* the handle in the light conductor. The conditions are exactly the same as in Fig. 3, so that the graphic representation of the e.m.f. and current can be indicated in the same way.

Turning Through 180 Deg.

Let us now rotate the loop through 180 deg., so that the black portion comes opposite the *S* pole (Fig. 8). E.m.f. and current reverse, as before, but the two commutator segments have also changed round under the brushes so that the direction of current through the external circuit remains in the same direction as for the first half-revolution of the loop.

This is clear from an examination of Fig. 9. A drawing representing the growth of the e.m.f. in the second half of the revolution is exactly the same as for the first half of the revolution *as far as the external circuit is concerned.* It is, therefore, shown on the same side of the line.

We are now in a position to see what the e.m.f. and current in the *external* circuit look like. Fig. 9 shows that we now have two distinct portions for each revolution of the loop.

Starting with the loop vertical, with the black portion at the top, the e.m.f. and current grow from zero to maximum with rotation through 90 deg. They then fall away to zero with the loop passing to 180 deg. In rotating the loop through a further 90 deg. to 270 deg., the values build up as before, and during the last quarter revolution to 360 deg. they again fall away to nothing.

Unidirectional Current

Now, although we have a unidirectional current in the external circuit, it can hardly be called a "continuous" current, as it obviously consists of two distinct pulsations per revolution of the loop. Only for very short periods are maximum e.m.f. and current being produced, and the power expended in the external circuit will be very small.

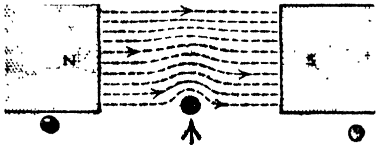


Fig. 10. Conductor moving upwards through the field, with lines wrapping around it in clockwise direction.

Getting Sustained Current

In the next chapter dealing with continuous current generators it will be explained how sustained voltage or current can be obtained in the external circuit during the whole revolution. Actually, the principle underlying this is merely to increase the number of rotating loops and sections on the commutator.

We do now see, however, that with fundamentally the same machine we are able to produce in the external circuit either currents which reverse at each half-revolution of the loop (alternating currents) or which remain in the same direction (continuous or direct currents).

The only alteration required at the generator is to provide two rings at the ends of the loop (slip-rings) for alternating current, or one split ring (commutator) for direct currents. In both cases brushes are necessary to collect the current and conduct it from the generator to the external

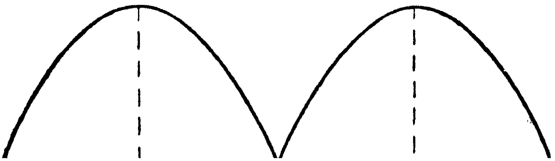


Fig. 9. Drawing which indicates the e.m.f. in a circuit connected through a commutator to a simple loop generator, during one complete conductor rotation.

In the very simple experiments

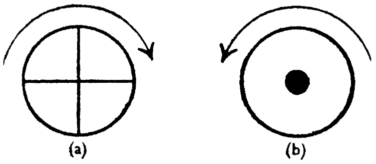


Fig. 11. Conventional signs for current (a) into and (b) out of the page. Arrows show direction of the flux.

described, the outside circuit has consisted merely of a meter. In practice, of course, the external "load" is provided by the lamps, motors, or other equipment which it is required to operate.

Looking Back

Before leaving this consideration of generator principles, it will be helpful to switch back a little and consider the lines of force passing between the magnetic poles as wrapping themselves round the rotating conductor, as has been briefly suggested already, instead of being cut by it. Thinking of the matter in this way, the lines are considered as being semi-elastic, which, in fact, they are, as far as purely imaginary lines *can* be. In wrapping themselves round the conductor, they follow it for a certain part of its travel.

In Fig. 10 is portrayed a conductor moving upwards through a magnetic field, and the lines are shown as curving round the conductor in clockwise fashion.

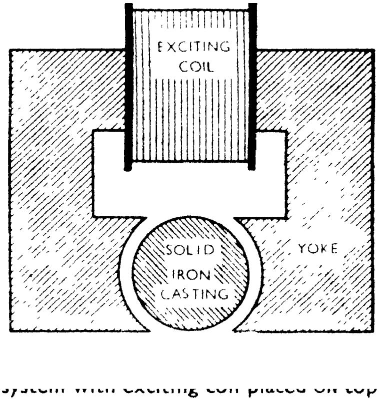
Current Direction

It has been explained in Chapter 3 that the passage of current along a conductor results in the appearance of magnetic lines of force surrounding that conductor. Conversely, the wrapping of lines round a conductor produces an e.m.f. and current. The direction of the current can again be ascertained by means of a very simple rule.

In Fig. 10 the lines are shown as moving round the conductor in a clockwise direction. Imagine an ordinary wood screw placed upon the point representing the conductor section and rotated in the same clockwise direction. The screw would be driven into the page, away from the person turning the screwdriver. That would also be the direction of polarity and of (conventional) current. Reversal of the lines, indicating the withdrawal of the screw, would result in a reversal of current direction.

Fig. 11 shows the conventional signs for current *into* and *out of* the page, and these can be thought of as the head and point of a screw. This simple rule, and Fleming's for determining the direction of e.m.f., meet all practical requirements of the engineer.

So far we have assumed the existence of a magnetic field between the two magnetic poles shown on large scale in our diagram. In practice a proper form of magnetic circuit requires careful



system with exciting coil placed on top member of yoke. Large air-gap is filled with a solid iron casting.

consideration. This applies not only to the shape which the "field magnets," as the magnetic system is called, will assume, but also the material of which they are made.

Field Magnets

It is hardly necessary to say that in practical machines, permanent magnets are not employed, only electromagnets. For the sizes required the latter are easier to make, cheaper, and more consistent in performance. The principles of the electromagnet have been described in Chapter 3.

The magnet frame, which will be described in detail later, is usually a casting of iron or steel. Cast-iron is much cheaper in manufacture, but it cannot be worked at a high magnetic density; that is to say, the number of magnetic lines which can be packed into each square centimetre of section with cast-iron is low, and will not exceed about 8000 lines.

With cast-steel, on the other hand, densities up to 15,000 lines per square centimetre can be obtained. Clearly, the greater the number of magnetic lines, the stronger the field and the higher the e.m.f. induced at a given speed of rotation will be.

Consideration of Weight

For a given field density in a generator, a cast-iron magnet system would be almost double the size of a cast-steel system, so that the weight also would be almost double. Where weight is a consideration, cast-iron frames cannot be used.

Again, if cast-iron is used for the poles, as distinct from the whole magnet system, the weight of copper wire that must be wound round them to produce the magnetic flux will be about three times that necessary if cast-steel be employed.

With modern designs it is possible to use a main frame of cast-iron while the actual poles are of cast-steel to produce the necessary density of magnetic lines without excessive weight of metal or copper wire windings.

In Fig. 12 a simple form of magnetic field system affording two opposed magnetic poles, such as we have already considered, is shown. This leaves the windings, which will be described later, exposed to mechanical damage, damp, and such like.

Two-pole System

An improved form of 2-pole magnetic system is seen in Fig. 13. It will be noted that the connecting portion of the magnet between the poles, called the yoke, is divided into two halves. This permits the use of cast-iron; as half the magnetic lines pass through each portion, a density of about 8000 lines per sq. cm. in each half equals 16,000 lines through the poles if the areas are the same. The actual pole pieces are of cast-steel to permit this high density.

It will also be noted that the divided magnetic yoke provides a strong framework for the machine; instead of one coil placed in an exposed position as in Fig. 12 we now have two coils inside the machine, one on each pole. This is now standard practice for small 2-pole machines, and will be dealt with in greater detail when the matter of excitation, or the turning of a piece of steel into a magnet, is considered. An advantage of this form of construction is

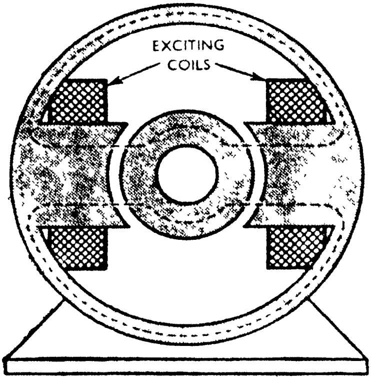


Fig. 13. Modern form of 2-pole magnetic system, with exciting coils placed one on each pole. The direction of flux is shown by the dotted lines.

that the moving conductors and the field coils are well protected against damage, and the entry of damp and dirt minimized. This has no little advantage, which will be realized more fully as we proceed.

Up to now the moving conductor has been considered as rotating in free air in a tunnel between the magnetic poles. Such a condition is quite impossible in any practical form of machine because the high resistance, called reluctance, of the air-gap to the passage of the magnetic lines, or flux as we shall now call them, would mean that a very great magnetizing force would be necessary to cause this.

Air-gap Reluctance

If we want anything in the nature of 15,000 magnetic lines per square centimetre to pass from the face of one pole to that of the other, means must be found to reduce the reluctance of the air-gap.

The problem is to bridge the gap with a material that will allow the magnetic flux to pass without serious opposition and, at the same time, permit the conductors to rotate without any kind of obstruction.

The solution is to mount the moving conductors on a rotating drum of iron or steel, of such size that the air-gaps between it and the pole faces are reduced to a minimum. It is not possible, of course, entirely to eliminate air-gaps, because there must always be some clearance between the stationary and rotating parts.

Rotating Drum

This rotating drum is illustrated in Fig. 14 and is seen mounted between the magnetic poles. In early machines the conductors in which the e.m.f. is generated were fixed to the outside of the drum and carried round with it. This form of construction exhibited serious disadvantages. For one, under heavy electrical load—or owing sometimes to the centrifugal force—the conductors were liable to fly off the drum and wreck the machine. For another, the presence of conductors on the outside of the drum necessitated a wide air-gap between the drum and the pole faces.

In modern machines the iron

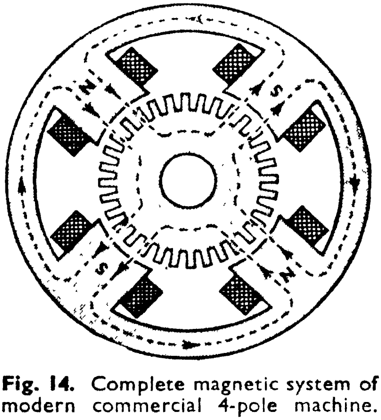


Fig. 14. Complete magnetic system of modern commercial 4-pole machine.

drum is slotted to receive the conductors, which can be rigidly wedged into position in the slots, with small risk of displacement. This design also permits the iron drum to be increased in size so that there is very small clearance between it and the pole faces and maximum magnetic flux passes across the air-gap.

The presence of this rotating iron or steel drum in the magnetic field is attended by a difficulty. It will be remembered that in Figs. 1 and 2 the production of eddy currents is illustrated. There it is shown that the passing of a magnet over a metal sheet produces rotating currents in the metal. Similar currents will be set up in the rotating drum, which forms a mass of metal moving in the magnetic field of our generator.

Heat Effects

Eddy currents are produced in the surface of the drum and flow through it from end to end. They cause heat and, worse still, distortion of our magnetic field.

If these currents were allowed to persist, the efficiency of the generator would be seriously reduced, not only on account of heating, but also because some of the power of the engine driving the generator would now be wasted in producing these unwanted currents.

A form of construction is adopted which reduces this trouble to a minimum, but which cannot entirely eliminate it. Instead of a solid casting of iron or steel for the drum, we build it of very thin sheets of metal which are threaded on to the shaft of the machine and bolted up tight to produce the size of drum required.

Before assembly, the faces of each sheet are treated with an insulating varnish, so that they are lightly insulated from one another. This prevents the passage of eddy currents longitudinally through the drum, although it cannot prevent the circulation of much smaller currents in each individual sheet.

Number of Poles

Most practical generators do not contain only one pair of magnetic poles, but have two, three or even four. The commonest form of construction is with two pair, which produces a 4-pole machine.

In Fig. 14 is drawn the complete magnetic circuit, known as the magnet system, of a modern commercial 4-pole machine. Reading in a clockwise direction it will be noted that the poles are alternately *S*, *N*, *S*, *N*. This means that the magnetic flux no longer passes right across the toothed drum making up the rotating portion of the magnetic circuit, but enters and leaves at an angle of roughly 90 deg.

The dotted lines indicate the mean flux path through the complete magnetic circuit. It will be seen that the flux divides through two paths from each pole through the external connecting ring, or yoke. The yoke may, therefore, be constructed of cast-iron, but each pole must be of cast-steel

Pole Pieces

The four poles, or "pole pieces," as they are called, are of separate construction from the magnet ring and are fixed to it by steel bolts. The coils used for magnetizing the poles are seen as a shaded portion round the pole pieces.

The ends of the pole pieces are shaped to fit more closely round the armature and to form an extension of the poles; these are known as pole shoes or pole faces.

At the moment we are concerned only with the magnetic system, and this may be briefly summarized from Fig. 14 as magnet ring or yoke, poles or pole pieces, pole shoes or faces, and the rotating drum which carries the moving conductors. Only very small air-gaps now exist in the complete magnetic circuit.

Method of Construction

In passing, it may be stated that the method of construction adopted for the rotating armature, building it up from thin sheets of metal, is often used also for the construction of the poles or pole pieces. Reactions from the rotating drum may induce eddy currents in the faces of the poles, and these are as disadvantageous as in the drum itself. Drums and poles constructed in this manner are said to be "laminated."

It is time to look more closely at the means by which the magnetic field is obtained. In some forms of generator, as, for instance, the magneto used for ignition purposes on motor-cars, the magnet system consists primarily of a strong permanent magnet, but as already suggested, for larger machines the use of permanent magnets is not desirable. There are several reasons.

Not Really Permanent

One is that, however good the material employed in their construction, permanent magnets are very rarely absolutely permanent, and even simple magneto magnets have occasionally to be remagnetized. More important, however, is the fact that the magnetic flux from a permanent magnet is not easily controlled and, from what has already been said, it will be realized that some means of controlling the flux density and, therefore, the generated e.m.f., is most desirable in commercial generators.

Practically all commercial generators obtain their magnetic flux by electromagnetism; that is, the placing of insulated wire coils round the poles and passing a current through these coils.

The source of current for this purpose may be from batteries, from another generator, or, most usual, by utilizing part of the output of the machine itself; examples of all these will be considered in due course.

Fig. 14 shows the position of the magnetizing coils in the case of the standard 4-pole machine. The process of turning a plain steel pole piece into an electromagnet by the passage of current round the coil is known as the "excitation" of the magnetic field. A field coil, as it is called, may produce "over-excitation" or "under-excitation," as may be required.

Ampere-turns

The purpose of the exciting or field coils is to produce a magnetic flux at the pole and, for this, a predetermined number of "ampere-turns" is necessary. As the term implies, the number of ampere-turns is the number of amperes flowing multiplied by the number of turns of wire round the coil. The greater the ampere-turns the larger the number of magnetic lines per square centimetre produced.

Eventually, a condition is reached where the iron or steel pole piece simply cannot accommodate any more lines, and the metal is said to be "saturated." When this point is reached, it is useless to go on increasing the exciting current, as no stronger field flux can be produced.

A current of 50 A flowing round a coil of 10 turns produces magnetic flux proportional to 500 ampere-turns. But so does a current of 1 A in a coil of 500 turns. It is, therefore, found sometimes that on each pole there are two coils, one made up with a fine wire winding, and carrying a comparatively small current, and another carrying a heavy current, necessitating a much larger conductor. Both types of field coil have the identical function—which is to produce magnetic flux by means of electromagnetism—but they achieve the requisite number of ampere-turns in different ways.

The calculation of the number of ampere-turns necessary in order to produce a given strength of magnetic flux in the poles is a matter of some complexity. Sufficient to say that various reactions in armature and field coils form complications that set apparently simple calculations at naught and they produce problems for the expert designer. The quality of the iron or steel used for the poles and the armature core, the depth of the core teeth, or, as we have so far called them, the slots, all have their bearing upon the result.

Magnetic Leakage

Another important factor is magnetic leakage and we will now inquire into this.

In Fig. 14 the magnetic flux is considered to be passing from the *N* pole through the armature core to the *S* pole. Generator design would be a simple matter if this happy state of affairs were to prevail in practice but, unfortunately, a fair part of the magnetic flux chooses to pass between the poles without touching the armature core. The most likely distribution of magnetic flux in a small 2-pole machine is shown in Fig. 15, from which it will be seen that quite a lot of the flux is lost.

This is one reason why multipolar machines are used today, as with more than one pair of poles it is possible to reduce magnetic leakage to a reasonable value.

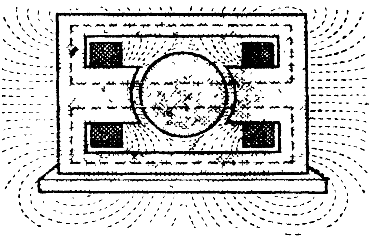


Fig. 15. Dotted lines show extent of magnetic flux leakage that is likely to occur with 2-pole design.

In the present state of knowledge, some leakage always remains. Even in the case of the machine illustrated in Fig. 14, a large proportion of the total flux that is produced by the field coils in the poles must be considered as wasted.

All flux which does not pass between the pole faces and the armature core must be considered as failing in its proper job, which is the provision of a strong field in which the rotating conductors can generate the desired e.m.f.

It is usually taken that with even the best-designed magnet system nearly 25 per cent of the flux produced in the poles will escape. In designing a generator, therefore, it is necessary to allow for the production of some 30 per cent more magnetic flux in the poles than is theoretically necessary for the generation of the required e.m.f.

This, in turn, means the provision of more ampere-turns in the field coils. Excessive magnetic leakage has a very adverse effect upon machine efficiency, and it has to be reduced by all possible means.

Armature Coils

The rotating conductors supported upon the armature core are called armature coils. The output from the simple generator dealt with in the early part of this chapter was very poor, in that the e.m.f., and, therefore, the current, was at its maximum for only a very brief time during one revolution. It is necessary to multiply the number of conductors so that a large number of such maxima appear during one revolution and, in practice, this is always done.

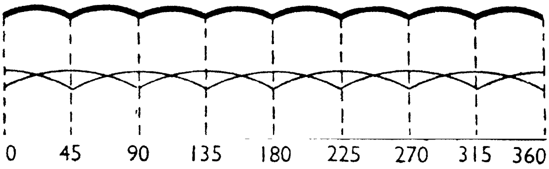


Fig. 16. Magnitude of e.m.f.'s generated in four loops, with 8-segment commutator, two segments per loop.

For instance, if there were four pairs of coils in series making up our rotating loop, the output would be as indicated in Fig. 16. In this case, it would be necessary to have eight commutator segments, with the ends of each loop connected to opposite segments.

The e.m.f. never dies down to zero, as there is always one loop in maximum "cutting" position. In the diagram the lower curves represent the induced e.m.f.'s in the individual coils, and the upper thick curve shows their resultant.

It is, for several reasons, a somewhat difficult matter to calculate the number of conductors required for any given output from a generator, or the speed at which they should cut the magnetic flux. One is, that even if the face of the armature core is covered with conductors, only a proportion of them is at any time passing under a magnetic pole and, therefore, producing an e.m.f.

It is usual to ignore the number of poles and to count all the conductors under all the poles as a basis for simple calculations. It is not correct to count all the conductors on the armature, as all are not under the poles and some for the time being are idle.

A rough guide to the generation of e.m.f. in any set of armature conductors is obtainable from the following formula:

$$\frac{R \times M_a \times T}{60 \times 10^8} = \text{volts},$$

in which R represents the revolutions per minute of the armature, M_a the number of lines of flux passing from the pole tips into the armature core and which, thus, influence the generation of the e.m.f., and T, the total number of conductors cutting this flux, that is, all those immediately under the pole faces. In passing, it will be noted that the top line of the formula rather suggests the word "armature" and this provides a useful reminder.

In the bottom line, the division

by 60 is in order to bring the seconds behind the calculation up to minutes, and thus fit in with revolutions per minute indicated by R; division by 100,000,000, or 10^8, is to bring the absolute units of e.m.f. up to volts, the standard unit.

The student may make up his own imaginary calculation by assuming numbers of conductors and revolutions per minute. It must be taken into account that with 10,000 to 12,000 magnetic lines per square centimetre of pole face, the total number of lines will depend upon the area of the pole face in centimetres.

Voltage Regulation

It is usual to work the magnetic circuit of practical generators at flux densities well under the saturation point for the material used for yoke and poles. If this were not done, voltage regulation of the machine by means of alteration in density, accomplished by varying the amperes of the ampere-turns producing the flux, would be difficult. It is not always convenient to alter the speed of the engine driving the generator; it is much simpler to raise or lower the excitation of the magnetic circuit and this has exactly the same effect upon the voltage output.

There are certain losses which take place in all generators and which cannot be entirely eliminated by good design. However large in section the armature conductors may be, they are bound to have some resistance, and when current is being drawn from the machine this resistance will cause a loss in voltage.

This loss is not constant, but depends upon the amount of current which is being taken from the armature. It may be calculated at any moment by simple Ohm's Law; the current in amperes multiplied by the resistance in ohms shows the loss in volts.

Assuming that a current of 100 A is being taken from the terminals of the machine, and that the resistance of the armature is ·05 ohm, then the voltage drop is 5 V. To produce 200 V at the machine terminals the armature conductors must generate 205 V.

The heat produced is proportional to the watts lost, which are current^2 × resistance, or 500 W, and is equivalent to the heat produced by a ½-kW radiator bar. This illustrates the great importance of adequate ventilation in the design of the generator.

With modern generators, a very high proportion of the mechanical energy applied to the driving shaft appears as electrical energy at the machine terminals.

In the case of a generator delivering about 500 kW (say, 2500 A at 200 V), the efficiency, or ratio of mechanical input to electrical output, would be as high as 95 per cent. With smaller machines, having outputs of 10 to 100 kW, about 90 per cent efficiency can be obtained. Generally speaking, machines delivering alternating current have higher efficiencies than those giving direct current.

Losses Sustained

By far the heaviest losses that occur in generators are due to the factor already mentioned, the voltage drop resulting from the resistance of armature windings and exciting coil windings. These are usually described as I^2R losses. Unfortunately, the energy which is dissipated in this way appears as heat. The difficulty of ventilating exciting coils and armature windings means that much of this heat tends to accumulate in the depths of the coils. If allowed to reach high temperatures it may cause damage to the insulation of the coils and windings.

Rating of Generators

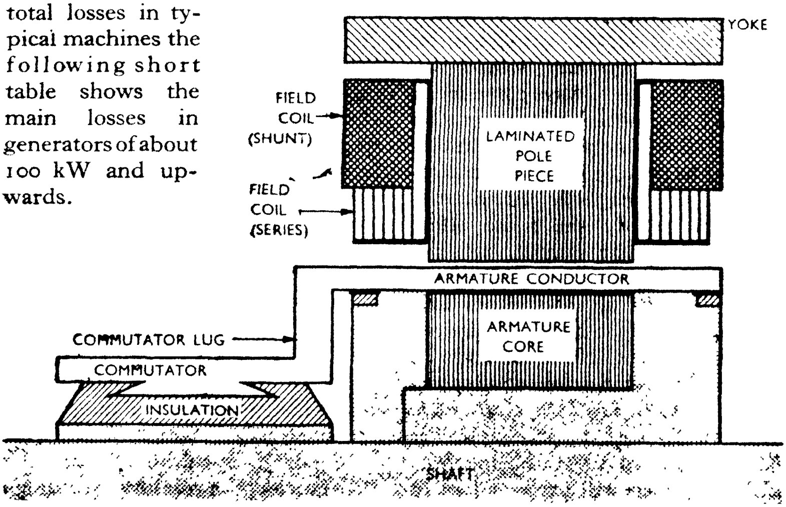
The output from generators is limited by the permissible temperature rise. Generators are rated in accordance with the requirements of British Standard Specifications, which say that machines must give their full rated output for a continuous period of six hours without the temperature of any part rising more than 40 deg. C. In addition, the machine must be capable of delivering up to 25 per cent overload without undue increase of temperature, even if this overload continues for two hours.

Without going deeply into the total losses in typical machines the following short table shows the main losses in generators of about 100 kW and upwards.

Losses Occurring in Typical Generator	*Percentage of Generator Output*
I^2R losses in field coils	
I^2R losses in armature windings . .	
Losses in armature core, in consequence of eddy currents setting up heating	2·0
Losses in commutator and brushes, caused by brush resistance and friction between brushes and commutator .	1·5
Bearing friction .	0·2
Windage, due to circulating air for cooling . .	

The total loss is, therefore, 7·9 per cent of the energy developed in the armature windings of the generator.

This may seem a quite small percentage, but if it could be improved by only 2 or 3 per cent it



SECTION OF SIMPLE D.C. GENERATOR

Fig. 17. At the top of this illustration can be seen a part of the field of the D.C. generator and it is this part which remains stationary. The whole of the armature (only the top half-section is shown) and the commutator rotate.

might mean the saving of thousands of tons of coal a year at a big generating station.

The efficiency of a generator is usually expressed as the ratio:

$$\frac{\text{output in watts measured at the terminals}}{\text{output in watts at the terminals plus all losses,}}$$

and is determined either by measuring the losses at varying loads, or, more directly, by measuring the mechanical input against the electrical output.

We have now cleared the way for a look at some of the practical points of a direct current generator. In Fig. 17 a section of the simple type of machine has been taken, and the main points to note are the laminated pole pieces and armature core, the two field coils, the armature conductor and the commutator.

It will be seen that the laminations making up the armature core do not extend in width beyond the pole pieces, and this is the core proper. The extensions beyond this are the metal clamps for securing the laminations in place.

Shunt and Series

Reference is made in the diagram to shunt and series windings, and these will be dealt with later; they are introduced at this time merely to show the general position of the field coils. In Fig. 17 the armature conductor appears to be mounted on the surface of the armature core; actually, it is sunk into the core slots. This may be more clearly seen from Fig. 18, where the smallness of the air-gap between the core and the pole face will be noted.

This small gap ensures that maximum magnetic flux passes from the pole face into the armature core, the necessity for which has already been stressed. A further point of interest is the large space provided through the armature core for cooling air, and similar ducts will be provided at the sides of the pole pieces, through the field coils.

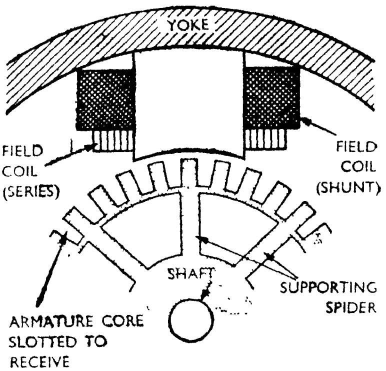


Fig. 18. Armature cores are usually built up from a number of iron stampings. These are clamped together to form the core and the notches line up and form slots. The conductors lie in these slots. In the above illustration conductors are not shown, but a clear impression is given of the air-gap between the core and one of the pole faces.

A point that will be stressed later may be noted at this time; the shunt field coil consists of a large number of turns of wire carrying a small current and the series winding consists of a small number of turns of very heavy cross section conductor. In Figs. 17 and 18 the latter appear as windings of copper tape, and this is the form the series windings often take.

We have now secured a clear idea of the principles of current generation—whether that current be applied to the external circuit as A.C. or D.C. When we come to practical machines we find that various difficulties arise, necessitating some very special features of both their design and construction.

CHAPTER 5

DIRECT-CURRENT GENERATORS

RING ARMATURES. FOUR-POLE MACHINES. DRUM ARMATURES. LAP AND WAVE WINDINGS. EQUALIZING CONNECTIONS. BRUSHGEAR. COMMUTATION. ARMATURE REACTION. INTERPOLES. COMPENSATING WINDINGS. FIELD EXCITATION. "BUILDING-UP" CURRENT. SHUNT-WOUND GENERATOR. ALTERNATIVE FORM OF CONNECTION. COMPOUND-WOUND MACHINES. VOLTAGE CONTROL. BATTERY-CHARGING SWITCHBOARDS.

DURING one revolution of a conductor in a magnetic field, the generated e.m.f. and, therefore, the current in the external circuit, are at a maximum for only a short time, so that very little energy is available and little electrical work can be done in the external circuit. As we have suggested, this can be overcome by multiplying the number of conductors. Another improvement would be to rotate the loop at very high speed, so that maximum e.m.f. appeared a large number of times in any given period; this could also be done by increasing the number of poles past which the conductors moved.

Number of Poles

In practice, excessive speeds are undesirable, so the solution of the problem boils down to an increase in the number of armature conductors plus an increase in the number of poles.

An armature, as we shall now call the complete assembly of steel core and conductors, must carry a definite number of conductors, depending upon the speed at which the armature will be rotated, the voltage which is to be generated, and the amount of flux which the magnetic field can produce in relation to the number of poles. The earliest form of armature winding,

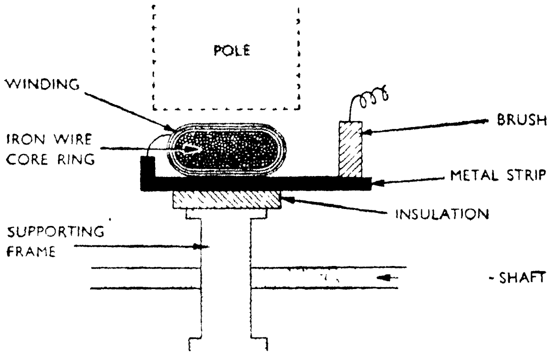


Fig. 1. Section of "ring" type armature, wound with continuous coil of wire with tappings to metal strips, upon which a pair of brushes makes contact, thus conveying the current to the external circuit.

and one which enjoyed a fairly long vogue, was known as the "ring," and this is shown in section in Fig. 1. An annular band of iron, at first a solid casting, and later, a small bundle of iron wires, thus anticipating the modern laminated type of armature, was used as the core, and round this a continuous winding of insulated wire was placed, closed upon itself.

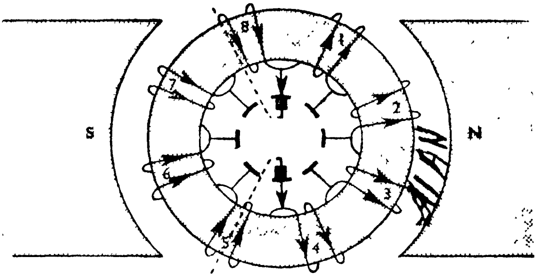


Fig. 2. Direction of e.m.f. and current generated in ring armature. Continuous winding is shown in eight sections, each tapped to a commutator segment.

Often, the windings were carried on the surface of the iron ring but, in some cases, the core was slotted to receive wound coils; it will be noted from Fig. 1 that the continuous winding is tapped at regular points, so that each section becomes, in effect, an individual coil. The tappings are connected to an equal number of commutator sections, which are seen projecting through the centre of the armature.

Ring-armature Action

Let us have a look at the action of this ring armature when placed in the gap of a bi-polar magnet system, as in Fig. 2. With clockwise rotation, the direction of the e.m.f.'s will be as indicated by the arrows placed in each coil. If these are closely followed it will be noted that the e.m.f.'s on the N pole side all form one total e.m.f., and flow from the bottom of the armature to the top.

In the same way, all the voltages generated in the coils opposite the S pole make one large e.m.f., flowing also from the bottom to the top. So we have in effect two separate e.m.f.'s moving from the bottom of the ring to the top.

With no external circuit connected to the commutator there would be no current flowing round this ring armature, in spite of the fact that the winding is continuous, because we have two equal and opposite e.m.f.'s. If, however, a brush be placed in such a position that it will tap this accumulated e.m.f. at the top of the ring, and a second brush be placed at the point from which, presumably, these two e.m.f.'s start, that is, the bottom of the ring, then we shall obtain a current in any wire connecting these two brushes. Of the current flowing in this wire, half will be due to the voltage generated opposite the N pole and half to that opposite the S pole.

This action may be easier to follow if the two halves of the ring winding, with their individual e.m.f.'s due to each section of the winding, be considered as voltages from small cells placed in a similar arrangement. This is shown in Fig. 3, and it will be noted that we have two parallel batteries not opposing each other but delivering a current to the external circuit.

Reversing Polarity

We have to stretch our imagination, however, to the point that when, during rotation, the small cells pass the extreme top or bottom positions of the ring, they immediately reverse themselves, and connect their positive poles where their negatives were connected before.

What we wish to make clear is, that the small individual e.m.f.'s generated in the several sections of the ring may be considered as connected in series in the same way that cells can be connected to provide a higher voltage battery. Also, that induced e.m.f.'s in armature coils can be connected in parallel to obtain greater currents, in the same way as can batteries, with the important proviso that the induced e.m.f.'s in the coils must be equal in magnitude, as must the e.m.f.'s of batteries connected in parallel.

In further considering the action of the ring armature, only the conductors on the *outside* of the ring are taken into account, as it is assumed that there will be no magnetic field inside the ring. This is lucky, for if there were a field as intense as that to which the external conductors are exposed, then we should get no e.m.f. at all; the inner turns would generate voltages opposing those in the outer turns.

It is always assumed that the magnetic flux through the ring is as shown in Fig. 4, from which it will be seen that the inner conductors move in a space free from flux, but in practice there is, of course, some magnetic leakage across this internal space. It is insufficient to produce any seriously adverse effect, however, and may be ignored.

Referring again to Fig. 2, we shall get a unidirectional current through the external circuit as indicated by the arrows in the wire connecting the top, or positive,

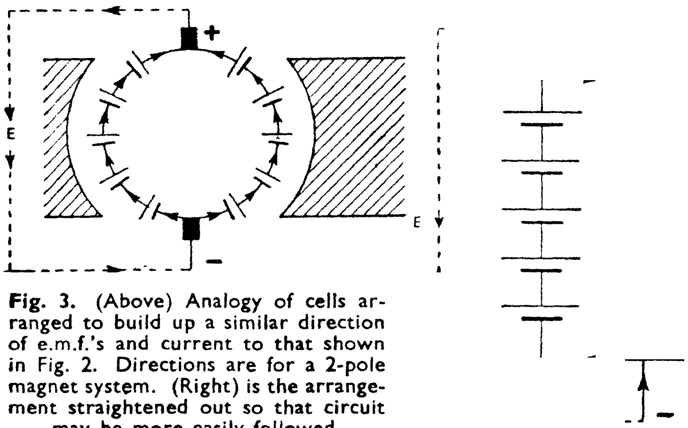


Fig. 3. (Above) Analogy of cells arranged to build up a similar direction of e.m.f.'s and current to that shown in Fig. 2. Directions are for a 2-pole magnet system. (Right) is the arrangement straightened out so that circuit may be more easily followed.

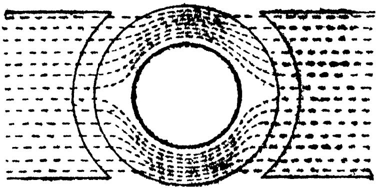


Fig. 4. Magnetic flux through a ring armature, showing that practically no flux appears in the centre of iron ring, and no e.m.f. can be generated there.

brush to the lower, or negative, brush. This current will continue to flow all the time the ring is rotating and the magnetic field exists.

This form of construction for armatures has now been superseded, although its principle is continued. Certain defects became apparent and are discernible from the description given above. There is too much idle copper winding on the ring; all that winding inside the ring serves no useful purpose, but adds unwanted resistance. This form of construction meant that expensive hand winding had to be resorted to in order to pass each turn through the ring. In addition, it was found difficult to make a mechanically strong armature and, under heavy load, the windings would tend to move about on the iron core; in early types, only the insulating varnish on the coils held them in place.

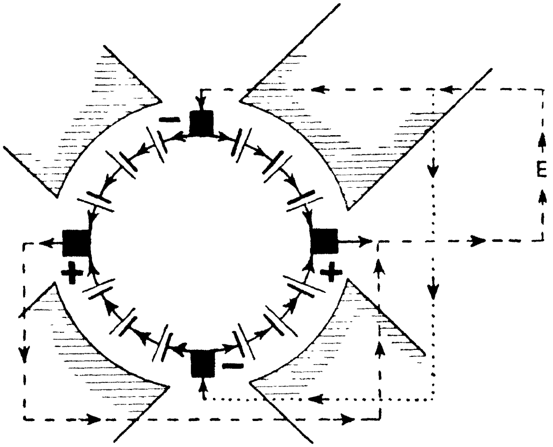


Fig. 5. Analogy of cells indicating direction of e.m.f. and current when the Fig. 4 ring armature is rotated in a 4-pole magnetic circuit. All that is necessary is to provide four brushes for the commutator in place of the original two, opposite ones being joined to form one pole.

Before leaving the ring armature, however, let us consider its action in the magnetic gap of a four-pole machine, the standard form of construction today for machines of medium output. Exactly the same ring can be employed and, using the analogy of the connection of cells in order to illustrate the direction of the induced e.m.f.'s, it will be noted that these now represent four sets of cells, as is drawn in Fig. 5.

Four e.m.f.'s

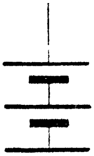
We really have double the arrangement we had with the bipolar gap; and four separate e.m.f.'s awaiting connection in some way, so that they may be able to cause a current to flow in the external circuit.

It is soon seen that if the two positive poles and the two negative poles be connected together, we have one main positive pole and one main negative available for output connections. This is clearer from Fig. 6, in which the arrangement of cells, representing the small individual e.m.f.'s generated in the ring, are shown connected in an orthodox manner. But it also shows clearly that when a 4-pole magnetic system is used, then we must also use *four* brushes on the commutator, as there are now four points at which the e.m.f.'s will have to be tapped.

Simplification

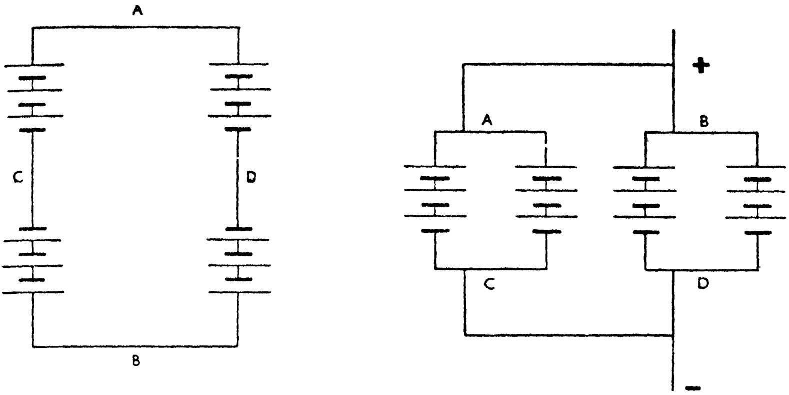
In Fig. 7 the arrangement of cells shown in Fig. 6 is rather straightened out, with the result that a somewhat complicated affair of cells in series and parallel can be followed more easily. It will be noted that we have a group of twelve cells, in two sets of three on each side, and if they were merely connected as indicated by the rectangle, no current would flow round the circuit. This is because on each side one set of three cells opposes the other set of three; and as both sides are equal in this way no current can flow from one side to the other.

If any current at all is to be drawn from this arrangement of cells, or e.m.f.'s as we should consider them, the common points, or negative poles, in the centre of each side line, must be connected together. In a similar manner, the positive terminals in the centres of the top and bottom lines must also be connected. From these two connecting loops we can now draw current into the external circuit, shown as *E* in Figs. 5 and 6. Clearly, the e.m.f. available for



EQUIVALENT ARRANGEMENT OF CELLS

Fig. 6. Showing the orthodox method of connecting the individual cells shown in Fig. 5. Each cell represents the e.m.f. of one armature coil.



STRAIGHTENING OUT THE ARRANGEMENT

Fig. 7. Cells shown in Figs. 5 and 6 simplified still further, enabling direction of e.m.f.'s and currents building up into external circuit to be more easily followed.

the external circuit will not be twelve times that of one individual cell. If the diagram be carefully followed it will be found that we have four sets of three cells in parallel. The total voltage cannot be more than three times that of any one cell, but the total *current* available will be four times that available from one cell, or one set of three cells.

It is necessary to completely master this arrangement of e.m.f.'s in series-parallel connection, as practically all modern armature windings follow this general arrangement.

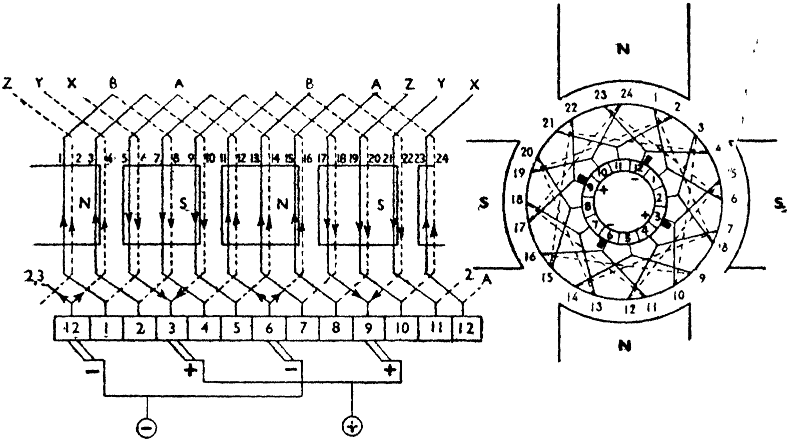
Drum Armature

The limitations of the ring armature are overcome in what is known as the drum type, with which there are two main forms of winding in common use for all commercial generators, and which will now be considered in detail. Certain special requirements of output necessitate modifications of these fundamental types, but they do not occur with sufficient frequency to demand study here.

In lap winding, as illustrated in Fig. 8, the armature coils are so connected that the finishing end of one coil is connected to a commutator segment and to the starting end of an adjacent coil situated under the same pole face, or in the same magnetic circuit, and so on until all the coils have been connected. It will be noted from the diagram that a series of overlapping loops is thus formed and, as a consequence, this form of winding is termed "lap" winding.

Assuming clockwise direction of rotation, the actual direction of e.m.f. and current can be followed easily from Fig. 8. The interconnecting of opposite pairs of brushes, which are of the same polarity, and which was suggested above in connection with the ring armature, is also shown.

An alternative form of winding is known as the "wave" winding, and this is seen in Fig. 9. In this, the finishing end of one coil is connected to a commutator segment and to the starting end of a



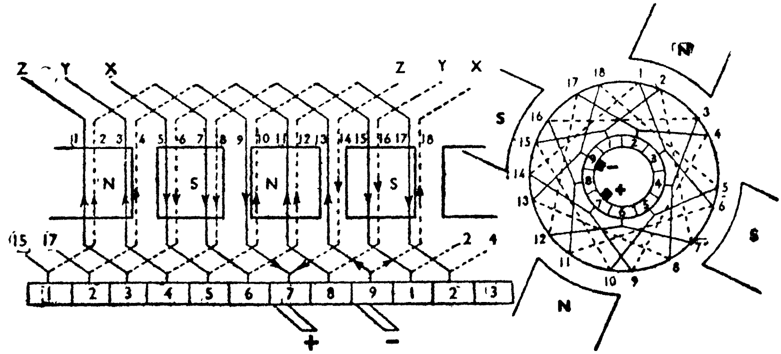
LAP WINDING FOR AN ARMATURE

Fig. 8. Illustrating a lap winding in a 4-pole magnet system. A series of overlapping loops is formed by this method of winding, thus the term "lap" is applied.

coil suitably situated in an adjacent magnetic circuit, and so on until all coils are connected. It will be noted that the interconnections between the coils progress continuously in one direction round the armature in a series of "waves."

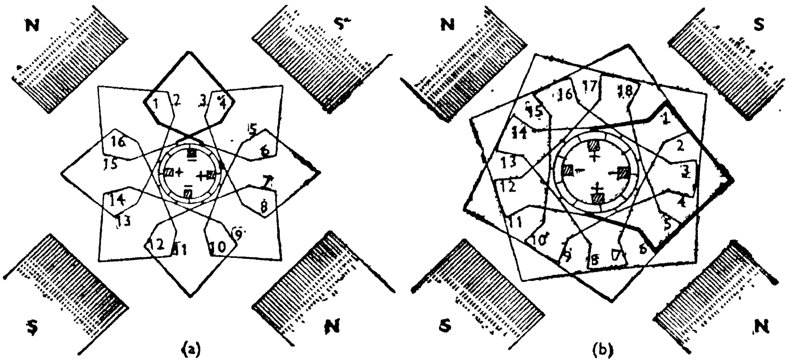
Comparing Methods

Current directions are shown in Fig. 9, but the two methods may be more clearly compared in Fig. 10, where they are shown side by side. With lap winding there are as many parallel paths for the current through the armature as there are poles, but with wave winding there are only two, whatever the number of poles. Thus, for equal conditions of voltage, speed, flux, number of poles, etc., the number of conductors required for a two-circuit wave winding is only $2/n$ of the number required for a lap winding,



SIMPLE WAVE WINDING

Fig. 9. Alternative form of winding known as "wave" winding. It will be noted that two brushes are used for a single circuit, and four in a double circuit (Fig. 10).



TWO METHODS OF WINDING COMPARED

Fig. 10. Comparison of armature windings with a 4-pole magnet system. At (a) is illustrated a lap winding, whilst at (b) is seen a double-circuit wave winding.

where *n* is the number of poles.

The current in each circuit of the wave winding is one-half the total current generated, whereas the current in each circuit of the lap winding is 1/*n* of the total current. From this it follows that lap windings are better suited for generators with outputs of large currents at low voltages, and wave windings for small currents and high voltages.

One of the chief advantages of the wave winding is that each of the circuits from brush to brush is brought under the inductive effect of *all* the poles, so that the total e.m.f. generated in each section is the same, even if the individual pole strengths differ slightly. On the other hand, with lap windings, the several parallel circuits may produce unequal e.m.f.'s, causing local currents to circulate through the armature windings. This action may be compared to the effect that would be obtained with unequal parallel circuits of cells.

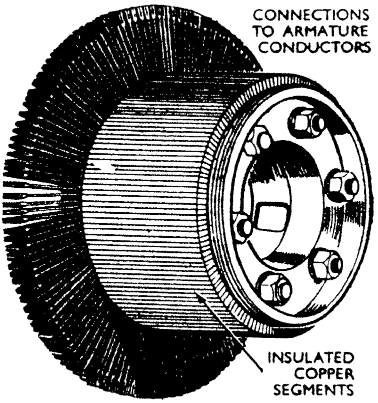


Fig. 11. Showing the method used in building up a commutator from hard-drawn copper segments clamped in insulating rings.

Equalizing Connections

To prevent the occurrence of these circulating currents, and especially their passing through the brushes, where they set up destructive sparking, it is usual to employ equalizing connections between those points of the winding that *should* be at equal e.m.f. These connections provide an alternative path for any circulating current, and tend to equalize the e.m.f.'s of the various parallel circuits of the lap winding. Lap windings are unsuitable for small machines, but

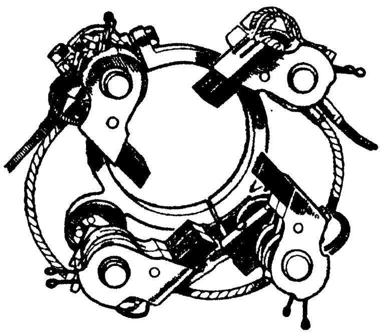


Fig. 12. Brushgear for a 4-pole machine. Note how carbon brushes are kept by spring pressure against the commutator.

are mostly employed on large machines.

Armature windings now consist of specially prepared sections of winding on formers, which are produced ready insulated for insertion and keying into the core slots, although in very small armatures hand-winding is still necessary.

Copper Segments

The commutator is built up of hard-drawn copper segments, rigidly clamped in insulating rings, shown in Fig. 11. The radial extensions of these segments serve a dual purpose, a means of radiating the heat produced in the commutator and an easily accessible form of connection for the armature con-

The brushgear for a 4-pole machine is illustrated in Fig. 12, in which carbon brushes, sliding easily in holders, are kept by spring pressure against the commutator.

The complete armature is shown in Fig. 13. The windings are secured in position by bindings of strong steel wire, three of which may be clearly seen. The ducts through the armature for ventilating and cooling are visible and, at one end, is the large-diameter fan used for forcing a cooling draught through the machine.

On the face of things, the problem of commutation, that is, the changing of the direction of the generated e.m.f.'s so that the external circuit receives current in one direction only, appears simple. Actually, it is a most complex and difficult problem.

It will be remembered that, in dealing with the ring armature and saying that its action was similar to a rotating set of cells (Fig. 3), it was mentioned that when any individual "cell" passed under the collecting brush on the commutator it immediately reversed its polarity.

The passage of the commutator segments under a brush is shown in a simple form in Fig. 14, and the varying current values for a total current at the brush of 100 A can be seen in (a), (b), (c), (d) and (e).

It will be noted that, in some cases, an armature coil is actually short-circuited under the brush,

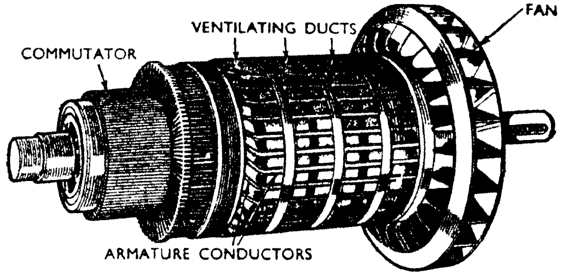
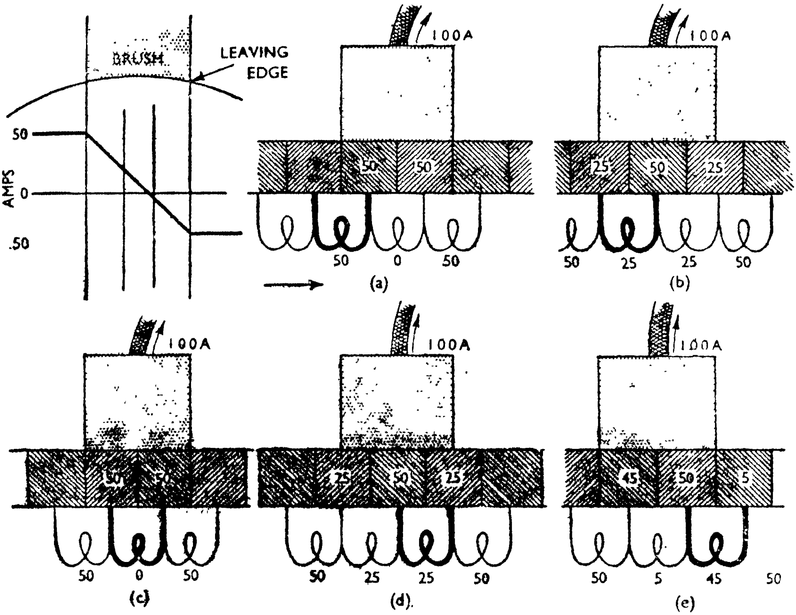


Fig. 13. Completed armature. Ventilating and cooling ducts through the armature, and large-diameter fan which forces cool air through the machine, are visible.



PASSAGE OF COMMUTATOR SEGMENTS UNDER BRUSH

Fig. 14. Variation in the current flowing between a carbon brush and the commutator segments when a current of 100 A is involved. Currents in the short-circuited coils under (a) and (c) are reduced by the resistance of the brush. The reactions of the commutating poles, or interpoles, cannot be shown diagrammatically, but they exert their influence to effect the above current changes sparklessly.

and this, plus a very complex and difficult problem associated with armature reactance e.m.f.'s (the nature of these will become clearer in later chapters), tends to set up destructive sparking. This difficulty demands the use of some form of brush exerting a fairly high resistance against both the short-circuit and reactance voltages. For this reason, carbon brushes are used for medium-output machines.

In practice, the carbon brush appears to exert a back-pressure against these e.m.f.'s to the extent of about one volt under each brush, and this feature is invaluable.

Copper brushes must be used for generators with high-current outputs; for instance, those used for electro-plating, where some thousands of amperes are delivered at the low pressure of 3-6 V, and also on modern turbo-generators of high speed, where other considerations have to be taken into account.

In any generator it is essential that commutation shall be sparkless and efficient. If heavy sparking takes place, not only will the commutator eventually be damaged and the brushes burned away at an excessive rate, but the heat generated will be carried by the armature conductors into the armature itself, where heating may in turn damage the insulation of the windings. To ensure that commutation is sparkless, it is necessary to place the brushes in what is called the "neutral" position—neutral, that is, with respect to the opposed armature voltages, not as regards the external circuit.

This neutral position is indicated in Fig. 3 as the point where the opposing e.m.f.'s meet, and where the most efficient collection of the generated current can be made by means of the brushes. As soon as current is taken from the armature, however, portions of the core are, in fact, turned into magnets. That is to say, with a fairly heavy current flowing round a section of the armature, the iron portion enclosed within that section becomes magnetized.

The effect of this armature magnetization is to cause distortion of the flux passing through the main magnet system; in fact, the armature now tends to drag the field flux round with it. This is more clearly followed by reference to Fig. 15, which represents the simple bi-polar field of Fig. 4 under working conditions.

It will be noted that a clockwise direction of rotation of the armature has now dragged the field flux quite out of position and, instead of our maximum e.m.f.'s being generated at the points 90 and 270 deg. as in the case of the simple loop, we shall now find them at approximately 120 and 300 deg.

The neutral position, the place where the brushes must be put in order to tap maximum e.m.f. sparklessly, is now a matter of some conjecture, especially as the amount by which the field is distorted is proportional to the amount of current being taken from the armature. In other words, if at some given output we find the best position for the brushes by trial and error, then, as soon as this output varies, owing to a higher or lower current being drawn from the machine, a fresh position must be found for the brushes.

Interpoles

Although Fig. 15 shows only the field distortion in a bi-polar field, yet the same thing exists in the standard 4-pole machine. It is clear that it is not possible continuously to shift the brush position with every small variation of output. Some form of field correction is necessary, and this is afforded by means of "interpoles," or "commutating" poles.

Examination of a commercial machine will disclose the fact that located between the main poles are smaller poles. With a 4-pole machine these small poles may number either two or four, and these are incorporated with a view to affording sparkless commutation with a fixed brush position. These poles, known variously as auxiliary, or commutating

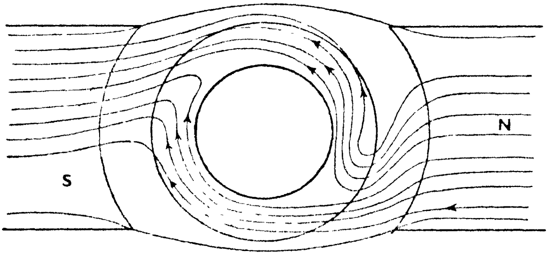


Fig. 15. How the magnetic field is distorted by armature reaction when the armature is carrying current. Amount by which flux is displaced depends upon the amount of current in the armature conductors. The theoretically neutral point is always shifting.

poles, but commonly as interpoles, are usually in line with the neutral axis between the main poles. They are excited by means of the full current drawn from the armature, so that their strength is always proportional to the load being taken from the machine.

By suitably proportioning these interpoles, the e.m.f. that is generated in the short-circuited coils under the brushes, during their passage through the reversing field produced by the interpoles, will tend to neutralize any e.m.f. that may be induced by the process of commutation. Sparkless commutation is, therefore, obtained at almost all loads without complete dependence upon high-resistance brushes, and the designer of the machine is enabled to load the armature right up to its temperature limit.

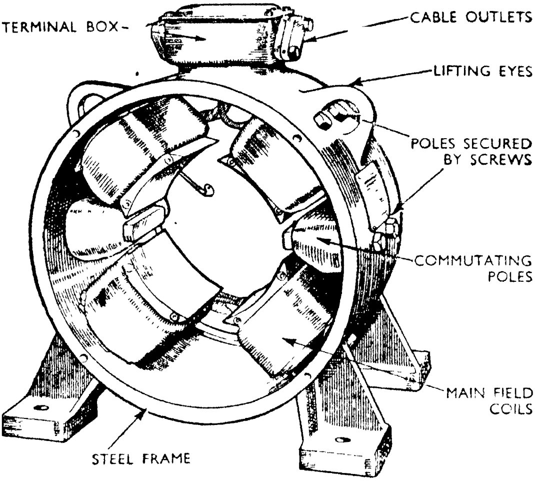


Fig. 16. Position of commutating poles, or interpoles, in standard 4-pole magnet system. In some cases, there may be four interpoles in a 4-pole machine.

The number of ampere-turns provided on the interpoles must be sufficient not only to neutralize those armature ampere-turns that are responsible for causing the field distortion, but also to pass the commutating flux through the air-gap and armature teeth.

The polarity of interpoles is, in the case of a generator, the same as that of the main pole just ahead in the direction of rotation.

The position and size of typical interpoles may be seen in Fig. 16, and it will be noted that, although this is a 4-pole machine, yet only two interpoles are provided. In some cases four interpoles will be found, located in the four spaces between the main poles.

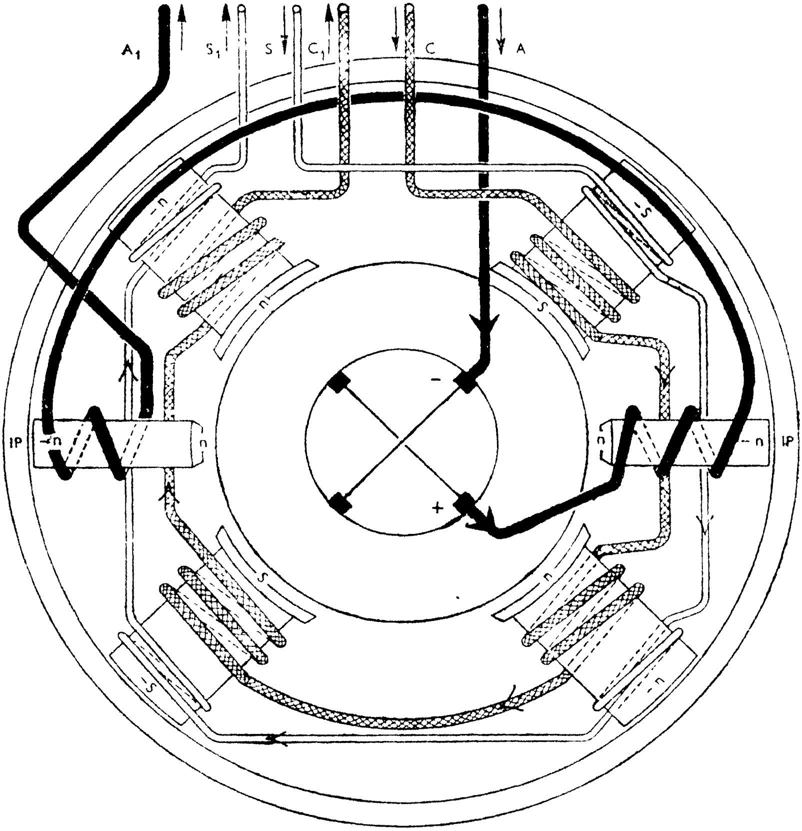
Other essential details of a practical 4-pole machine are also seen in Fig. 16, and the internal connections may be seen in Fig. 17. These latter will be dealt with in detail later but, in passing, it may be noted that armature and interpoles must always be treated as one circuit.

When generators are required to supply heavy currents with a weak excitation of the magnetic field, as, for instance, with reversing rolling mill plants, the provision of commutating poles and the use of carbon brushes do not suffice to afford sparkless commutation.

It is, therefore, necessary to provide a compensating winding in addition, and this is placed in slots in the pole faces. By connecting this compensating winding in series with the armature it can be made to neutralize the ampere-turns of the armature windings. This prevents the armature causing distortion of the main field.

Exciting Current

All usual connections for the excitation of magnetic poles in the standard 4-pole generator are shown in Fig. 17. It was stated earlier that the current necessary for excitation might be taken from another generator. This is done only in special cases, as, for instance, generators required to deliver large currents at low voltages, and where the tapping of the machine's own output would be unsuitable. Such a generator is illustrated in Fig. 18 and is one designed to supply 5000 A at 3 V; it is driven by means of an alternating-current motor (left) and has a separate small



CONNECTIONS FOR EXCITATION OF MAGNETIC POLES

Fig. 17. Current directions and windings for a standard 4-pole magnet system as shown in Fig. 16. (*A*) is the armature and interpole circuit, which must always be treated as one circuit; (*S*) shunt, or fine-wire winding; and (*C*) series, or heavy-conductor winding. The latter two may be utilized separately or in conjunction.

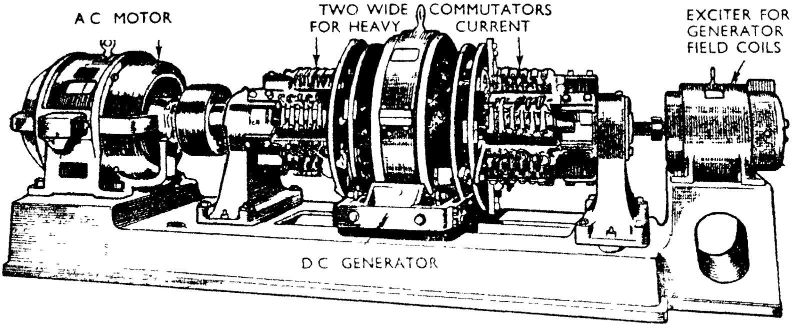
generator for exciting its field (right).

The great size of the commutator will be noted, and also that it extends on both sides of the machine; this is necessary when such large currents have to be handled. In fact, the size of a commutator is often an indication as to the magnitude of the current the machine is designed to deliver.

Reverting to Fig. 17, there appear to be three main windings on the various poles shown, but, as stated above, the interpole winding, connected in AA, may be neglected for the time being. This is, after all, merely a corrective winding, and has no real bearing upon the production of the main field flux, which is the function of the field coils proper. This leaves two separate windings on the main poles to be considered, those marked S_1 and S, and C_1 and C.

The windings S, indicated as small wires, are known as the "shunt" windings and do, in fact, consist of coils made of a great number of turns of small wire. The windings C, on the other hand, are known as "series" windings, and usually consist of a very few turns of heavy gauge wire.

From what has been said previously, it is known that an equal number of ampere-turns may be produced with a coil of many turns with a small current, as with a coil of few turns and many amperes. The precise function of these two coils has to be studied in detail, however, as they are not just placed there in their two forms in order to provide variety for the maker.


A C MOTOR
TWO WIDE COMMUTATORS FOR HEAVY CURRENT
EXCITER FOR GENERATOR FIELD COILS
D C GENERATOR

GENERATOR DELIVERING A LARGE CURRENT AT LOW VOLTAGE

Fig. 18. This type of generator supplies 5000 A at 3 V and is driven by an A.C. motor (left), and has a separate small generator for exciting its field (right).

The current for the excitation of the poles is normally taken from the machine's own output. This may sound a paradox, as until the coils have been excited, and produced some flux in the poles, presumably there can be no output. In practice, however, once the field coils have been excited, the poles retain a small amount of magnetism; this is sufficient to start a small e.m.f. in the armature. With new machines, it is often necessary to apply the first excitation with a battery.

Assuming that the armature is rotating, the small residual magnetism of the four main poles

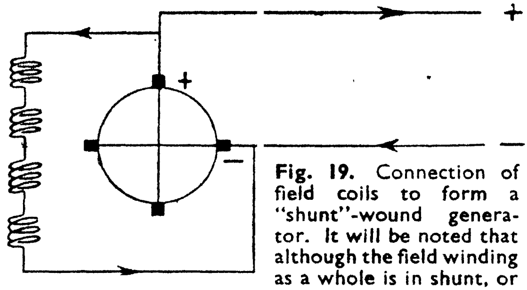


Fig. 19. Connection of field coils to form a "shunt"-wound generator. It will be noted that although the field winding as a whole is in shunt, or parallel, with the armature, yet the individual shunt field coils are connected in series with each other. The four coils are those in (S) circuit in Fig. 17.

causes a small e.m.f. to appear in the armature, and this would be detectable by a voltmeter on the outgoing lines from the armature A_1 and A.

If the shunt field winding, S_1 and S, be now connected to A_1 and A, a small current flows round the field windings due to S circuit, and the small residual field is strengthened. This again results in a higher e.m.f. in A circuit, with increased current through the S circuit, until the cumulative effect is complete and the machine is developing its full voltage. This feature is known as "building-up" and, in a simple manner, permits the use of a portion of a machine's own output for the purpose of exciting the field coils.

It will be realized, however, that it is most important that the current in S circuit be passed round it the correct way, or the small residual magnetism of the poles will be destroyed instead of being built up. The current directions are shown in Fig. 17, so that in order to produce the correct polarity it is necessary to connect S to A_1 and S_1 to A.

We have now produced a shunt-wound generator, in which the field winding is in shunt, or parallel, with the armature. In effect, the electrical connections are as indicated in Fig. 19; and this circuit may be easily followed in Fig. 17.

It will now be clear that if the shunt field exciting coils are made up of a large number of turns of small wire, then the amount of current utilized for the excitation of the machine will be small. It will be remembered that ampere-turns, upon which the magnetizing effect depends, may be small in amperes and large in turns, or large in amperes with a small number of turns.

The actual field current in this case is kept as low as possible, for two reasons. One is that whatever current is used for excitation must come out of the total current generated by the machine, and the more that is used for excitation the less will be available for the external circuit, where the work has to be done.

Another reason is that with low current density in the field coils,

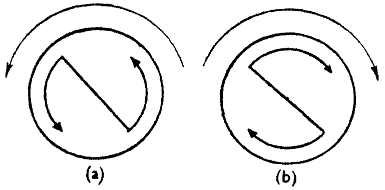

(a) (b)

Fig. 20. In (a) the formation of the letter N with arrows at its extremities, coinciding with the direction of current, shows that the pole face towards the reader is N, or north; in (b) the letter S can be formed in the same way, showing that with reversed current flow the polarity is now S, or south.

the I^2R losses are kept down and deep-seated heating in the field coils is minimized. Both reasons really mean that the efficiency of the machine is improved with low excitation current.

Determining Polarity

At this point, a simple rule for finding the polarity of an electro-magnet, knowing the direction of current round it, might be considered. In Fig. 17 certain polarities with given current direction are indicated, and this simple rule will apply to them all. It is given in Fig. 20, is easily memorized and it affords all the guidance necessary in order to determine polarity, knowing the direction of current flow, or vice versa.

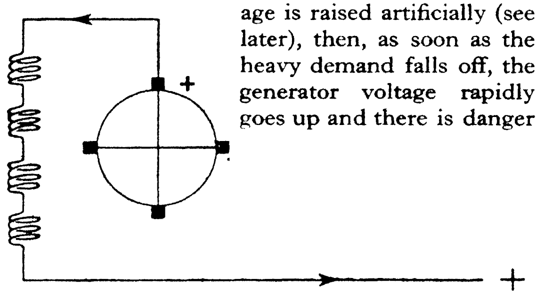


Fig. 21. Connection of field coils to form a "series"-wound generator. The four field coils—circuit (C) in Fig. 17—are themselves in series with each other and in series with the armature output. It is the latter circumstance which decides the description of "series" wound as applied to a generator.

Current may now be drawn for the external circuit from the two leads marked positive and negative in Fig. 19, which correspond to the terminals A_1 and A in Fig. 17. With constant speed, the voltage will remain steady, and the shunt-wound generator, as this type is called, is a very popular form. In fact, for some purposes, such as storage battery charging, the use of the shunt-wound generator is universal.

One shortcoming of the shunt-wound machine is that under most conditions of heavy load, or when the generator is approaching the limit of its output, the voltage tends to fall. This is due to the fact that the increase of current in the armature conductors causes an increased voltage drop in those conductors, as has already been considered, and any fall in voltage at the brushes must mean a lower e.m.f. available for the circuit round the field coils.

A reduction in exciting current means a further drop in the brush e.m.f., so that this effect tends to become cumulative, and a point is reached when the machine's nominal voltage output cannot be maintained. If the machine's voltage is raised artificially (see later), then, as soon as the heavy demand falls off, the generator voltage rapidly goes up and there is danger that lamps may be burned out.

Let us see if any alternative form of connection in the various windings shown in Fig. 17 could be utilized, ignoring the *S* circuit; what about the *C* circuit, which appears to pass round all the field coils in the same manner as the *S* circuit?

The windings comprising this circuit consist of a few turns of heavy section conductor only, so if equivalent ampere-turns are necessary, equal to those set up by the *S* circuit coils, then a heavy current must be sent round the *C* circuit. This heavy current might be obtained by connecting the *A* and *C* circuits *in series*, as then the whole of the machine's output passing to the external circuit would first traverse the field coils of *C* circuit.

The simple electrical circuit of this arrangement is shown in Fig. 21 and produces a type known as a series-wound generator. It will be clear that all current passing through the armature now passes also through the *C* circuit field coils. What will be equally clear is that, until there is some form of external circuit connected, no e.m.f. can be generated by the machine, as there will otherwise be no exciting current for the fields.

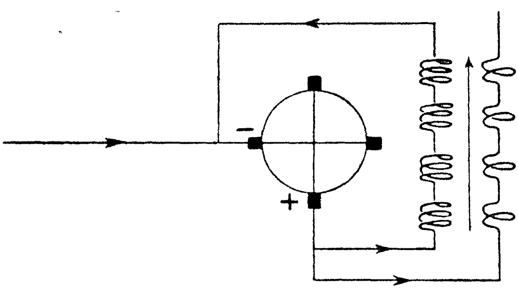


Fig. 22. "Compound"-wound generator, utilizing both forms of winding shown in Figs. 19 and 21. Current directions round both sets of coils must be the same, or one winding will oppose the other winding, instead of assisting in producing magnetic flux in the direction that is required.

Series-wound Generator

This type of generator was used to a great extent in the early days of electric lighting, especially for street lighting with arc lamps. These lamps were left connected to the generator, probably some eight or ten in series, and when lighting was required the generator was started up, being shut down when no further lighting was necessary.

The series-wound generator has very few applications today, in spite of the fact that it possesses one very important characteristic: its voltage actually rises with any increase in external load. This would be expected, as all current taken into the external circuit does its bit in providing excitation for the machine.

It is not possible to make very much practical use of a machine when its voltage varies up and down in accordance with the load being drawn from it. But it would be very useful if its ability to increase voltage with increased load could be utilized in other types of generators, and in practice this is done.

In Fig. 22 the connections of what is known as a compound-wound generator are given. In this type the advantages of the shunt winding and the series winding are combined.

The main excitation is taken over by the shunt winding, and this means that an e.m.f. is available as soon as the machine is running at its correct speed. At ordinary loads, the series winding, which is now merely a few turns round each pole, has little or no effect upon the main field excitation, but as soon as the load becomes heavy, then the additional ampere-turns round each pole maintain the voltage at the correct level.

Compound-wound generators may be arranged so that they keep a level voltage, whatever the output, in which case they are known as level-compounded. They may even be provided with a large number of series windings on each pole so that with increase of load the voltage also increases. In such a case the machine is said to be over-compounded. This step is taken in order to overcome voltage drop in the connecting cables, which drop naturally increases with heavy loads.

With an over-compounded generator a perfectly steady voltage may be maintained at the point of application of the supply, the generator automatically compensating for voltage drop in its own windings and in connecting cables.

In Fig. 17 we find all the internal connections necessary for a modern compound-wound generator. The main field excitation is provided by circuit *S*, consisting of a large number of turns of wire round each pole and carrying a small current. The additional ampere-turns necessary to maintain a level voltage at all outputs up to the machine's limit are provided by the small number of turns round each pole of the *C* circuit, the connections being made as in Fig. 22.

Direction of Current

It will be clear from Figs. 17 and 22, that the current direction round each pole due to circuit *C* must be the same as that for circuit *S*, or we shall have one winding opposing the other. That would mean a drop in voltage with increased load, and not the maintenance at the proper level which we are seeking.

Circuit *A*, the armature with the two interpoles, has already been dealt with to some extent, but we are now in a position more clearly to comprehend the function of the latter. With any increase in load on the machine, the pole flux will be strengthened by means of the series windings, which are, as shown by Fig. 21, in series with the armature.

Any increase in pole flux means, in turn, larger displacement of the magnetic flux through the armature, owing to increased armature reaction and, therefore, any corrective means that are to be applied must also be increased.

Flux Displacement

By placing the interpoles in series with the armature, they also become in series with the compound or series windings on the poles, and any increase of current in one circuit is automatically an increase in all. Therefore, it follows that with any strengthening of the main pole flux and any increase in armature reaction, the strength of the interpoles is increased in equal ratio, with the result that flux displacement is corrected to the desired extent.

Although this matter of flux distortion and correction by interpoles has been dealt with in a very simple manner, yet it is a highly complex phenomenon, and provides the generator designer's greatest problem.

With correctly placed brushes, and the right type of brush, coupled with careful interpole design, the generator we have been considering should run with complete absence of sparking at the brushes or undue heating in armature windings right up to its limit of output, whatever that may be. If sparking is taking place, one of these necessary forces is not present, and this fault will usually be found to be due to wrong brush position, or to the use of brushes which are of unsuitable resistance.

At all costs, heavy sparking at the generator brushes must be eliminated, or not only will excessive heating of the commutator, and, by conduction, the armature windings, take place, but heavy wear on brushes and commutator will result.

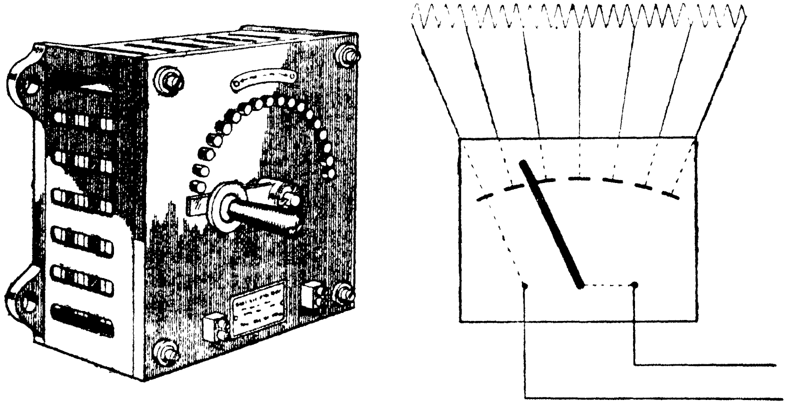
To a lesser extent, the brush pressure on the commutator may be responsible for sparking; if this is too light, the brush will tend to jump away from the commutator with any slight inequality, or under vibration. If the brush pressure is too heavy, excessive frictional heating and losses will occur.

Control of Output

As has been previously mentioned, the e.m.f. generated depends upon two main factors; one, the speed at which the conductor is moved in the magnetic field, and the second, the strength of that field. In practice, it is not easy to control the speed of rotation of the armature in a generator except by varying the speed of the driving engine, and this cannot be done within close limits. In addition, there is usually some convenient speed at which the engine will run most economically, and it is undesirable that it should be varied from this speed merely to adjust the voltage output of the generator.

Therefore, it is customary to vary the magnetic flux output from the poles, and this can be accomplished in a very simple manner. An adjustable resistance is inserted in the main field excitation circuit, that is, the shunt field circuit, and the amount of current flowing round this circuit can be closely controlled. It follows that the voltage output of the machine can be governed by an adjustment of this variable resistance, and a device known as a shunt field regulator will be found on every switchboard controlling the output from a direct-current generator.

For convenience in operation, the shunt regulator is remote from the generator, and placed in some easily accessible position. The



CONSTRUCTION OF A SHUNT REGULATOR

Fig. 23. Spirals of resistance wire are arranged in an iron case and ventilated to dissipate heat. The amount of resistance in circuit can be varied by the contact handle on the front, which passes over metal studs mounted on a slate base, and to which various points of the resistance spiral are connected. Shunt regulators are used for regulating the amount of current passing through shunt field coils.

simplest type of regulator is illustrated in Fig. 23, and consists of wire spirals mounted in a metal frame; these are suspended vertically to allow them to dissipate the heat produced by the passage of the field current.

In large generator installations, operation of the shunt regulator may be automatic, but, in other cases, the variation in resistance is achieved by moving the handle over the studs until the correct value of resistance is found. This will be indicated by voltmeter connected to generator terminals.

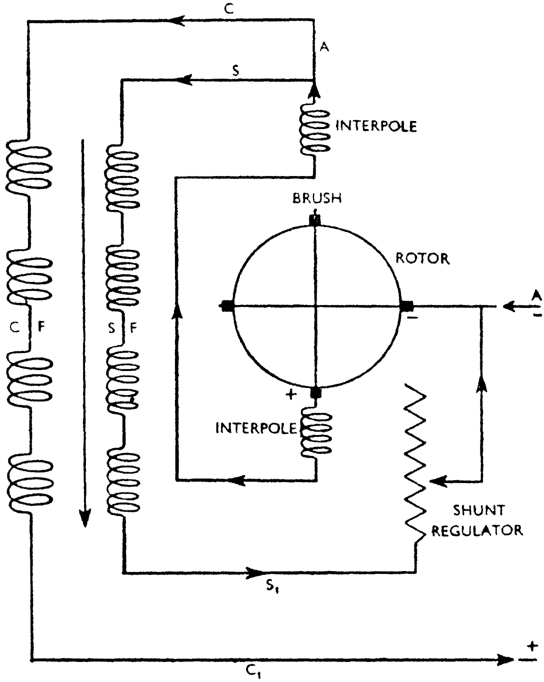


Fig. 24. Compound-wound generator, using both the windings shown in Figs. 19 and 21, and all in Fig. 17.

The complete compound-wound generator, as far as its connections and voltage control gear are concerned, is illustrated in Fig. 24. The interpoles appear on each side of the armature, which may be compared with the arrangement seen in Fig. 17, coupled with the connections indicated in Fig. 22.

A suitable controlling switchboard for this type of generator is portrayed in Fig. 25, and consists of ammeter and voltmeter, double-pole fuses, double-pole switch, and shunt regulator.

The ammeter indicates the current flowing, the voltmeter shows the voltage at which the generator is operating, and whether it requires any adjustment by means of the regulator. The two fuses protect the generator against excessive overload, and the switch is used to disconnect the generator from the circuit. The two smaller fuses shown at the top of the board are for the protection of the voltmeter.

For certain purposes, the shunt-wound generator holds the field; an example is battery charging. It will be interesting to examine the reasons why the more attractive compound-wound machine, with its level voltage characteristic, is not used for this purpose.

Reverting to Fig. 22, it will be seen that if by any chance the engine driving the generator developed a fault and stopped, a heavy current would flow back from the battery through the generator. But, whereas this current would flow round the shunt field circuit in such a way that the polarity of the generator would not be reversed, yet in its passage through the series or compound winding it would tend to destroy, and then reverse, the field polarity. This would mean that when the machine was again started up it would generate an e.m.f. in the reverse direction to normal, and if still connected to the battery it might cause serious damage to it. The ability of the shunt-wound generator to maintain correct polarity with reverse current flow ensures its almost universal use for battery charging, although a compound-wound generator may be adapted for the purpose by cutting out or short-circuiting the series, or compound, winding.

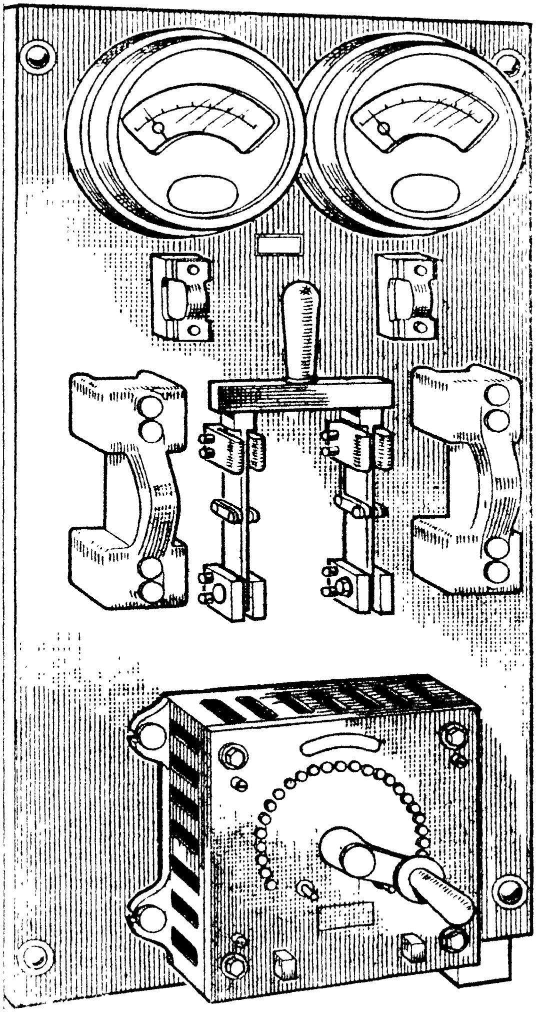


Fig. 25. Switchboard for controlling generator (Fig. 24), used for D.C. (Top) ammeter showing current passing to external circuit, and voltmeter. (Below) two fuses for protection of voltmeter. (Centre) double-pole switch for disconnecting circuit, and two large fuses for protection against overload. (Bottom) shunt regulator.

A rather more complicated type of switchboard is necessary for the proper control of a shunt-wound generator supplying current for the charging of a stationary battery, and this is shown in Fig. 26. It consists of an ammeter for indicating the current flowing from the generator into the battery, with a second ammeter for showing the current being drawn for the external circuit for lighting, or other purposes. One voltmeter only is necessary, as this can be connected as required to the generator or battery circuits by means of the small switch seen below the instruments.

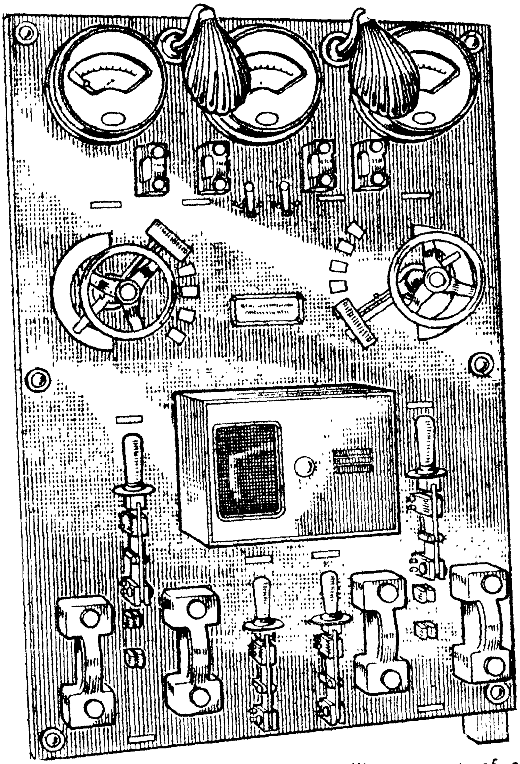


Fig. 26. Switchboard for controlling output of a shunt-wound generator used for battery charging.

Protecting Devices

The two small fuses in the centre protect the voltmeter, and the two bracket lights used for illuminating the instruments are supplied through the two outer fuses. Below these small fuses are two regulating switches, enabling the end, or regulating, cells of the battery to be brought in or out of the charging and discharging circuits respectively.

The large device in the centre of the board is an automatic battery switch, designed to disconnect the battery from the generator immediately the latter ceases to supply current and the battery current commences to flow back through the generator. The two outer controlling switches now have alternative contacts below, that is to say, they are change-over switches, enabling the external lighting circuit to be connected direct to the generator and the battery cut out.

The normal switches are in the centre, and the two pairs of heavy fuses at the bottom of the board control the incoming current from the generator and the outgoing current from the battery respectively.

The internal connections of this controlling switchboard are drawn in Fig. 27, and it will be noted that, in this instance, the shunt regulator is mounted near the generator and not on the board.

Breaking the Field

There is one further important accessory that may be found on switchboards used for the control of shunt- or compound-wound

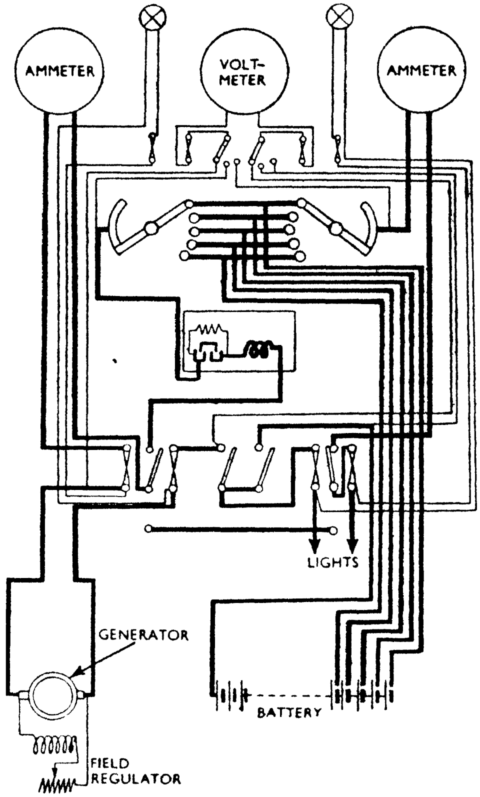


Fig. 27. Internal connections of switchboard shown in Fig. 26, and showing battery and generator connected. The shunt regulator is not on the board, but is mounted near the generator. The two battery regulating switches can be operated independently of each other—their positions need not coincide as in the diagram.

generators, and this is the field-breaking switch. It will be remembered that when the magnetic circuit that is associated with a coil of wire suddenly collapses, for instance, when the current is switched off, then a very high e.m.f. may be induced in that coil. This phenomenon is known as self-induction, and the better the magnetic circuit the higher the induced e.m.f. will undoubtedly be. The shunt field circuit of a generator is made up of a large number of turns of wire on the individual field coils, all connected in series, and these coils are included in a highly efficient magnetic circuit. If the field circuit were suddenly broken, a very high e.m.f. of self-induction would build up in these field coils and it might reach a magnitude sufficient to break down their insulation or cause other damage.

Special Switches

It is essential that the field circuit should never be broken except by means of the special switches designed for the purpose, and it will be imperative that, before the shunt circuit is broken, it is connected across a non-inductive resistance. Any e.m.f. induced in the field coils will be safely dissipated across this resistance, and will not be allowed to build up into a highly dangerous voltage.

The modern compound-wound generator with level characteristic is almost self-regulating in practice and, unless the load is wildly fluctuating, it can be relied upon to operate at a steady voltage.

At the same time, very close voltage control is sometimes necessary, especially for generators supplying current for excitation for turbo-alternators or other large generators and, in such cases, automatic voltage regulators are employed.

CHAPTER 6

HOW D.C. AND UNIVERSAL MOTORS WORK

SIMPLE ELECTRIC MOTOR. MAGNETIC FIELD. PRACTICAL MOTORS. TYPES OF ENCLOSURE. VENTILATION. ARMATURE AND FIELD WINDINGS. FIELD COIL CONNECTIONS. BACK E.M.F. EFFECT OF LOAD. BURNING-OUT OF ARMATURE. SERIES, SHUNT AND COMPOUND-WOUND MOTORS. SPEED REGULATION. POWER DEVELOPED BY D.C. MOTORS. REVERSAL OF ROTATION. UNIVERSAL MOTORS. COMMUTATION IN D.C. MOTORS. STARTING GEAR. MOTOR DRIVES.

THE principle upon which a direct-current motor works is very simple. If a conductor is placed in a magnetic field and a direct current passed along it, then that conductor tends to move in a certain direction. The tendency is greatest when the conductor is placed at right angles to the flux.

The force with which the conductor attempts to move, and which is known as the torque, or turning effort, depends upon two factors : one, the strength of the magnetic field, and two, the strength of the current which is being passed along the conductor. With a weak field, and a small current, the tendency to move may be hardly perceptible, but with a strong field and a heavy current the immediate effort when the current is switched on is very violent.

The simplest form of D.C. motor is suggested in Fig. 1, and it will be noted that this consists of the familiar loop, mounted so that it is free to rotate in a magnetic field. The ends of the loop are connected to the split ring, or commutator, and two brushes make contact with this commutator. These are for the purpose of conveying current into the loop, and the source of the current may be a battery or the public supply mains.

The rule for determining the direction in which the loop will rotate when a current is passed is as simple as that shown earlier, which was for use in connection with electric generators. In the case of motors, however, the *left* hand is used for the purpose. As before, the forefinger is placed along the flux lines with the second finger pointing in the direction of current in the loop. The resultant movement of the conductor is in the direction indicated by the thumb.

Direction of Flux

In the case of Fig. 1, the direction of flux is from right to left, from *N* to *S*, and, in the case of the right-hand conductor, the current is flowing away from the commutator; for that reason, this particular conductor, therefore, tends to move *upwards*.

The left-hand conductor is subjected to magnetic flux in the same direction as the right-hand conductor, but the current is flowing towards the commutator. Its direction of movement, therefore, is

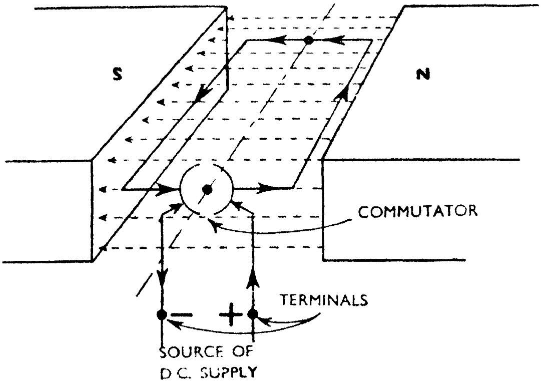


Fig. 1. Simple form of electric motor consisting of pivoted loop in a magnetic field. When the terminals are connected to a source of D.C. supply, current will flow around loop in direction of arrows.

downwards. In practice, continuous rotation will take place if the loop is sufficiently heavy and has enough momentum to carry it over the dead spots. These occur where the loop passes from the influence of one pole to that of the other, and the commutator segments are being transferred from the positive pole of the battery or mains to the negative pole. These neutral points occur when the loop is perfectly vertical between the poles.

Torque Effect

As stated above, the turning effort, or torque, is dependent upon the strength of the magnetic field. When considering the generator we found that the magnetic flux is not constant in a simple bipolar field such as that shown in Fig. 1 but is strongest immediately opposite the centre of the poles and weakest at the tips. The magnetic lines are cut with greatest speed at the centre of the pole faces and when the loop reaches the vertical position it is merely sliding along the magnetic lines and not cutting them.

This effect is apparent in the same way in the electric motor outlined in Fig. 1. The torque is greatest when the loop is immediately opposite the centre of the pole faces, and falls off as the loop approaches the vertical, eventually falling to zero. Clearly, if we want to construct a motor with a continuous torque proportional to the current, then we must increase the number of loops and, consequently, the number of commutator segments, as was done in the case of the D.C. generator.

Corresponding Problems

Other problems associated with the motor will be found to correspond to those previously discussed in connection with the generator. For instance, the strength of the

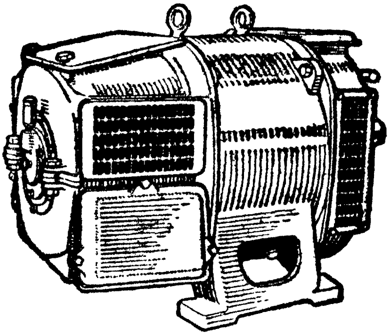
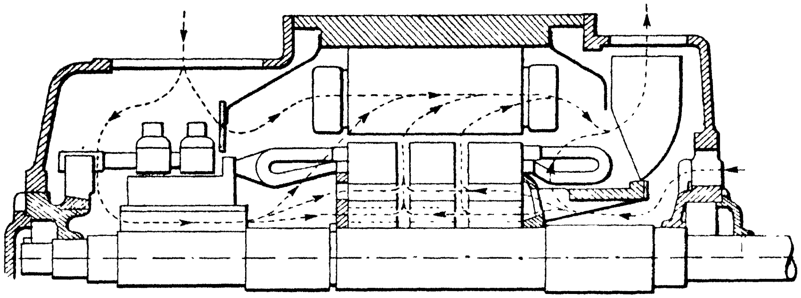


Fig. 2. Screen-protected motor in which no attempt has been made to exclude dust or fluff from the windings. It is suitable for most forms of electric drive and permits ample ventilation.



VENTILATING SYSTEM SHOWN IN SECTION

Fig. 3. Diagram showing the ventilation system embodied in motor illustrated in Fig. 2. Arrows indicate direction of air passing into machine and expelled by fan.

magnetic field must be as high as possible to afford maximum torque for a given current strength, and so we must mount the loop or armature conductor on an iron or steel drum to reduce the air-gap to a minimum.

So that constant torque may be produced, the number of loops or armature conductors must be multiplied, and it may be expected that an armature constructed as previously described would be suitable for our motor. In addition, if this armature were mounted in a magnetic field, such as was found suitable for the D.C. generator, then we might have all the requirements for an efficient electric motor.

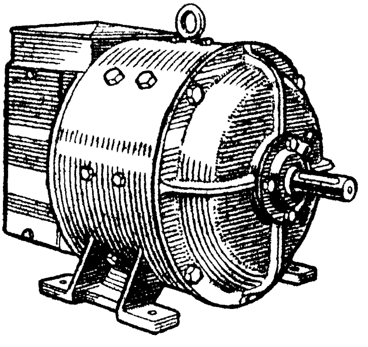


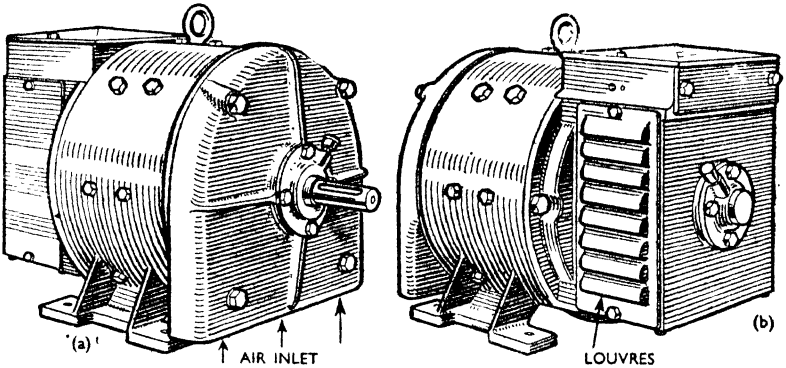
Fig. 4. Totally-enclosed motor in which the main means of cooling is by radiation and internal air circulation.

This is, in fact, the case, and there is no difference whatever in the construction of dynamos and motors; if current be applied to an electric generator it will run as a motor. Most, but not all, commercial generators may be used as motors without modification; the exceptions are few, and will be dealt with later.

Motor Protection

It will be found, however, that, as a rule, the same efficiency cannot be obtained, owing to the necessity for more closely protecting the motor. A generator is usually placed in a suitable position and mechanical protection for the coils and armature may be reduced to a minimum. On the other hand, motors have to work in conditions of dampness, dirt, chemical fumes, and liability to mechanical damage and, therefore, protection must be adequate.

As an instance, a motor rated at 5 h.p. when equipped with a light screen protection for its windings, may deliver no more than 3 h.p. when totally enclosed for use in a dusty situation. This is due to the fact that the output of a motor is



PIPE-VENTILATED MOTOR

Fig. 5. (a) Fresh clean air is brought to the motor by piping and drawn in through a big inlet. (b) Air is then expelled through louvres or taken away by pipe.

governed by its temperature rise under load, and this generation of heat can be controlled only by means of ventilation.

Since the problems of enclosure and ventilation assume prominence in the case of the D.C. motor, let us look at the methods adopted.

The commonest form of enclosure is seen in Fig. 2, showing a screen-protected motor. It will be noted that while adequate mechanical protection is provided for the coils and windings, yet under the influence of the ventilating fan mounted on the armature, dust and fluff can be drawn into the windings and ventilating ducts. The ventilating system is seen in section in Fig. 3, and it will be observed that some of the air ducts, especially through the armature, are small, and can be easily obstructed.

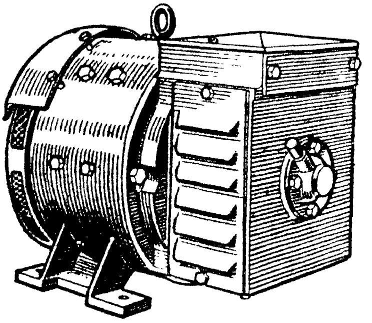


Fig. 6. Drip-proof motor, similar to the screen-protected type, but having protection against dripping moisture.

Method of Enclosure

In dusty situations it is necessary to use a totally-enclosed motor (Fig. 4). With this machine, cooling can be only by radiation from the outer casing, although some degree of internal air circulation may be arranged. Totally-enclosed machines are used only where absolutely necessary, owing to the much reduced power output available with the permissible temperature rise.

Where fumes are likely to prove harmful to the motor windings, a form of enclosure known as pipe-ventilated is used, and two views are given in Fig. 5. Air from a clean source is brought to the motor by piping and connected to the large air inlet casing shown at (a); after passing through the motor windings the warm air is expelled through the louvres shown at (b).

It is not necessary to employ a totally-enclosed motor in damp situations and the type illustrated in Fig. 6 is often used. This is known as a drip-proof enclosure and is, in essentials, a screen-protected type with guards arranged against the ingress of dripping moisture.

Easy of Access

For most purposes, the screen-protected motor of Fig. 2 is adequate, as it is desirable to have easy access to commutator and brush gear for cleaning and maintenance. This feature will be noted in Fig. 7, and the terminal box is shown in Fig. 8.

The four heavy terminals are the armature and series connections, and the two lighter terminals the shunt field connections. These will be dealt with in fuller detail later.

It is not proposed to describe in any detail the methods of armature winding adopted for D.C. motors, as they consist of the lap and wave types dealt with in Chapter 5. It need be said only that in all cases the armature windings are of low resistance and heavy current-carrying capacity, as it is obviously useless to provide an armature in which current flow is restricted, and energy wasted, by resistance.

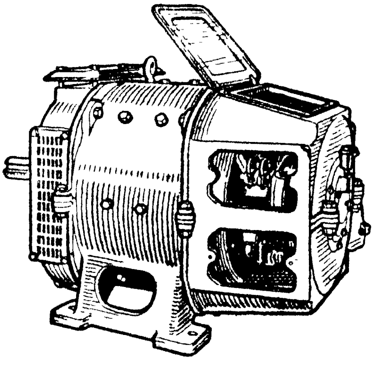


Fig. 7. Guards have been removed to afford access to the commutator and brushes in this screen-protected motor.

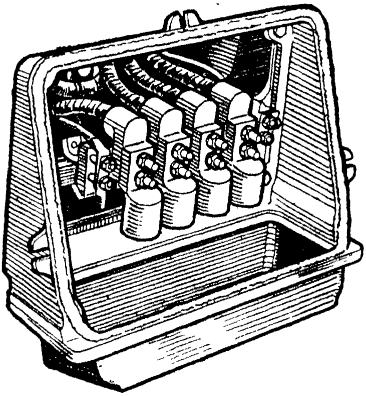


Fig. 8. Terminal box of motor shown in Figs. 2 and 7. The outer small terminals are the shunt field connections, and the four heavy terminals are the armature and series field connections.

Field excitation is very important. Although the three methods previously dealt with—shunt, series, and compound connections of field coils—are universally used, their respective advantages and effects are quite diverse.

Field Coil Connection

Let us consider the three methods of field coil connection in the same order as before. Fig. 9 shows the shunt method; for simplicity one field coil only is indicated, and the field is considered to be due to a bi-polar magnetic system. In practice, the connections would be as described and illustrated for the shunt-wound generator.

It will be seen that when the main D.C. supply is switched on to

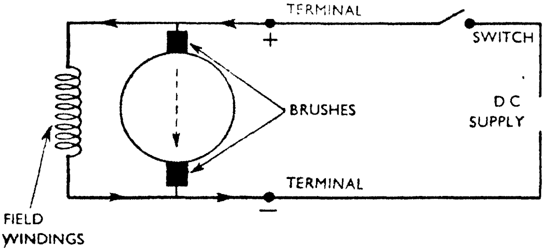


Fig. 9. Circuit of shunt-connected motor, the field windings being in parallel, or shunt, with the armature. Arrows denote the current direction.

the motor by the switch, current flows round two circuits connected in shunt, or parallel. One circuit is provided by the field coil, or coils, and the other by the armature.

Now, this is a very undesirable combination, a high resistance in parallel with a low resistance, and it might be expected that the whole of the current would flow round the low-resistance armature. When it is realized that the resistance of the field coils may easily be one thousand times that of the armature, the reason for the elaborate starting gear that is described later begins to be seen.

Current Flow

For the present, however, we will assume that a current will flow round the exciting circuit, represented by the field coils, as well as through the armature. Under these conditions the armature commences to rotate.

The armature increases its speed of rotation rapidly until it reaches a point of stability. This steady speed depends upon a number of factors, designed speed, the load on the motor, and so on, dependent upon the drive for which it is re-

A rather curious phenomenon can now be observed. The armature takes a much greater current when starting, and running slow, than it does when it reaches full speed and is doing its job. In Fig. 10 some idea of this drop in current is given.

Armature Resistance

The ammeter may show a reading of only 5 A when the motor reaches steady speed. How is this possible with a low-resistance armature connected to a 200-V supply? According to Ohm's Law, assuming the armature resistance to be

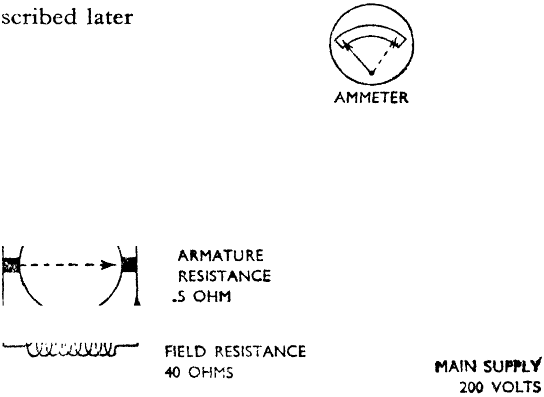


Fig. 10. Showing how an ammeter in circuit with a D.C. motor will indicate a current far smaller than would be expected according to Ohm's Law. Total value of resistance is less than ·5 ohm, but with a pressure of 200 V only 5 A pass, owing to the fact that the rotating armature generates a back e.m.f. which is working in opposition to the mains e.m.f.

·5 ohm only and neglecting the field coil resistance for the moment, the current indicated by the ammeter should be 200/·5, or 400 A.

The answer is that when the armature rotates, and in view of the fact that it consists of a number of coils mounted on an iron armature rotating in a magnetic field, it operates as a generator. The e.m.f. that it generates is in opposition to that applied to the motor from the supply mains, with the result that the e.m.f. available to drive current round the armature coils is much reduced.

Resultant Force

This will be clearer from Fig. 11, in which the multiple armature e.m.f.'s are again shown as cells of a battery. The e.m.f. of the supply is indicated as eight cells, and at 1·5 V per cell this amounts to 12 V. Inside the armature a back e.m.f. of "six cells" is set up, and this amounts to 9 V. The resultant of these e.m.f.'s is, therefore, 12 — 9, or 3 V, and this is all that is available to force current through the armature.

The analogy must not be pressed too far, however, as we have to imagine that current is being forced through the cells representing the armature by virtue of the fact that the supply voltage is higher. Also, the armature e.m.f. is shown as steady when made up of cells, whereas in a motor it is varying according to the speed of rotation of the armature and the strength of the magnetic field.

Reverting to Fig. 10, we are now in a position to appreciate why the armature current may be as low as 5 A. It explains why the voltage at the motor brushes is sufficient only to force 5 A through the assumed resistance of ·5 ohm, and this would be 5 × ·5, or 2·5 V. If the applied voltage from the mains be 200 V, then the back e.m.f. generated by the armature will be 200 — 2·5, or 197·5 V.

It will be appreciated that this back e.m.f. is confined to the armature and does not extend beyond the brushes. The field coils remain connected to the full mains voltage.

If, while the motor is running at steady speed, a brake is placed upon the shaft or pulley, tending to slow up the motor, then we shall note an increase in current passing by means of the ammeter in Fig. 10. This is because slowing up the armature makes the back e.m.f. fall, and it may now amount to no more than 196 V. This means that the e.m.f. now at the brushes is increased from 2·5 to 4 V, and an increased current through the armature results.

This feature enables the electric motor to adjust itself automatically to the load placed upon it, and the current drawn from the supply is in proportion to the load. When running light, a motor takes very small current, as only sufficient is needed to keep it rotating against bearing friction and windage caused by the ventilation.

Effect of Load

A small increase in load slows the speed down slightly, with a slight increase in current; a heavier load slows up the speed still more, and with a further reduction of back e.m.f., current through the armature again increases.

An excessive load, amounting to the stalling of the motor, causes a very heavy current to be drawn from the mains, as the back e.m.f. disappears. The only limiting factor will be the ohmic resistance of the armature windings and, as we have already seen, this is of necessity very low. Complete "burning-out" of an armature will follow the application of an excessive load unless precautions are taken by means of protective gear to prevent this.

This heavy current at stalling speeds is common to all D.C. motors, whatever the type or form of field connection, shunt, series or compound. It is particularly serious with the shunt-wound motor, however, because excessive current taken by the armature causes a loss of voltage in the supply wiring and this reduces the voltage applied to the field coils.

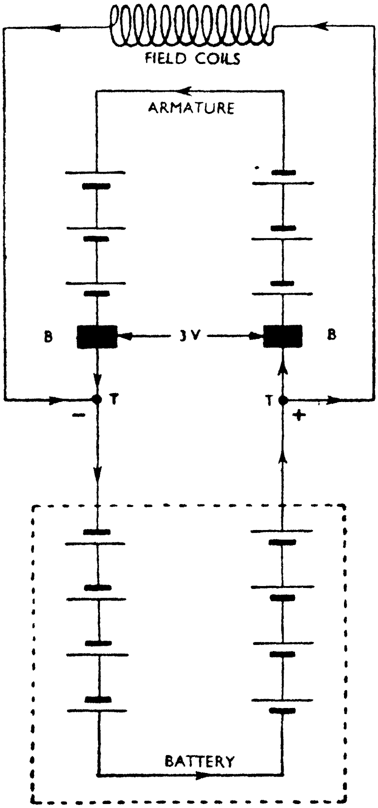


Fig. 11. Owing to generator action of armature, an e.m.f. of 9 V is in opposition to the main supply of 12 V, making the resultant e.m.f. 12 minus 9 V at the brushes of the motor.

Loss of Power

Any reduction in current in the exciting circuit means some loss of ampere-turns, with a weakening of the magnetic flux output from the poles of the magnetic circuit. This in turn means a drop in power exerted by the motor just at the time when power is most needed, at times of heavy load.

Maximum magnetic flux is necessary at times of starting and heavy loads; but, unfortunately, it is just at these times that a shunt-connected motor chooses to starve its field coils of current, due to no fault of its own, but owing to volt drop in the connecting cables.

Shunt-wound Advantages

All the same, the shunt-wound motor finds many applications in the driving of machinery, especially that connected for driving to line shafts by means of belting. The shunt-wound machine exerts a reasonable starting torque, with little more than full-load current, and its speed is almost constant. It cannot be used in the simple form, however, for drives demanding heavy starting effort, such as is required for electric trams, for instance, and some alternative form of field connection is advisable.

A motor with a very high starting effort, or torque, can be obtained by adoption of the series method of winding, seen in Fig. 12. Here, armature and field windings are in series. Any heavy current demanded by the armature, as at starting or times of heavy load, must also traverse the field coils, producing a very strong magnetic flux just when it is most wanted.

In our consideration of the series-wound generator we found that a series winding consisted of a small number of turns of heavy section conductor, designed to carry a very heavy current; from this we may infer that the series winding of a motor is of equally heavy current-carrying capacity and will deal safely with the heavy armature currents required for starting against heavy loads.

Series Motor Characteristics

When first switched on, the series motor puts forth a very high starting effort, and for this reason it finds almost universal application for the driving of trams, electric locos, cranes, and similar machinery. But it has a very serious drawback, instability under varying loads. This is because varying current through the armature also causes similar variation in the field strength.

Any change in speed due to varying load means proportional variation in the back e.m.f. in the armature, and as armature and field windings are now in series this back e.m.f. affects the current in *both* windings.

The back e.m.f. now chokes back the mains e.m.f. applied to both armature and field. With any increase in speed the increased back e.m.f. causes a weakening of the field. This in turn means that the armature must rotate at a still higher speed in order to generate sufficient back e.m.f., and the effect is progressive.

In most applications of the series-wound motor, the drive is by gearing and not by belts. Cases have been known of series motors having thrown their belts, and the subsequent rise in speed has burst the armature by centrifugal action.

In spite of its valuable characteristic associated with a high starting and overload torque, it is clear that some stabilizing control must be applied to the series-wound motor before it can find wide application for general drives. As in the case of the D.C. generator, salvation is found in a combination of shunt and series windings, the resultant motor having steady characteristics with high starting and overload capabilities.

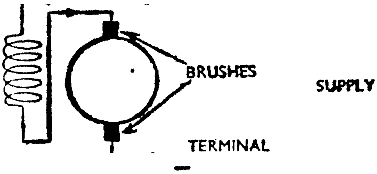


Fig. 12. Connections of series-wound motor. Current passes through the field coils on its way to the armature, and by this means the field is energized, and magnetic flux produced.

Compound-wound Motor

The problem is a little more complicated with the motor than with the generator and Fig. 13a gives the standard form of connection for the compound-wound motor. This should be compared with Fig. 22, Chapter 5.

The ideal form of connection would be with the series turns round the field coils *opposing* the shunt turns, as this would provide a motor with almost constant speed under all variations of load. At times of heavy load, when armature and series turns are carrying heavy current, the shunt field would be weakened and under all conditions of load practically constant speed would be obtained.

In practice, however, it is found that with heavy overload a compound motor's series field windings may entirely overcome the shunt field, if connected in opposition, and the result might be a reversal of direction of rotation. In consequence, series windings are almost invariably connected so as to assist the shunt windings. This gives us a stable motor with good starting and overload characteristics but does not secure constant speed.

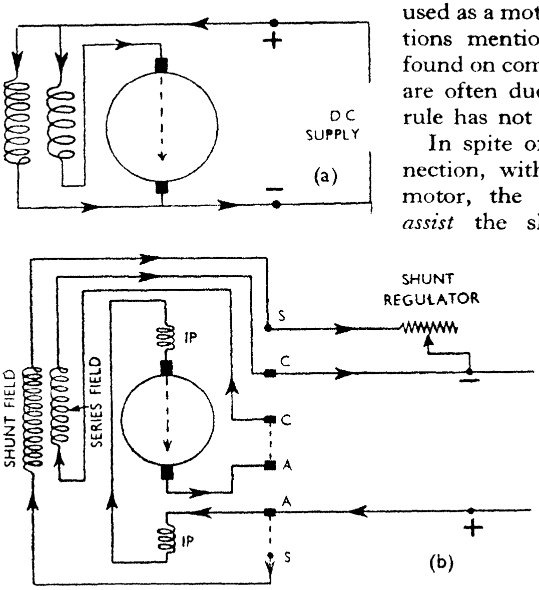


Fig. 13. (a) Normal arrangement for windings of a compound-wound motor. The ordinary winding of the shunt motor is retained, with a few boosting turns of heavy conductor in series with the armature. (b) All windings of a compound motor, with interpoles. With a 4-pole machine there would be four interpoles, four shunt field coils and four series field coils, but for clarity only two interpoles and one shunt and one series coil are shown. Note normal position for shunt regulator which controls the speed of the motor.

Earlier it was stated, with a proviso, that if current be applied to a generator it will run as a motor. The compound-wound generator is the exception. Comparison of Fig. 13a, below, and Fig. 22 of Chapter 5 shows why. In the case of the compound-wound motor the series winding is in the reverse direction to that of the generator. Before a compound-wound generator can be used as a motor its series field winding must be reversed. Otherwise the series field will oppose the shunt field when used as a motor, with the complications mentioned above. Troubles found on compound-wound motors are often due to the fact that this rule has not been observed.

In spite of the reversal of connection, with both generator and motor, the series field windings *assist* the shunt field windings. This is due to the fact that with the generator, current is coming *out* of the armature, and with a motor it is going *into* it.

All essential windings and connections for a compound-wound motor are found in Fig. 13a, and the several circuits may be easily traced in the practical arrangement shown in Fig. 13b.

The compound-wound D.C. motor is employed for the majority of drives;

if a series-wound or shunt-wound machine is required it can be adapted from the standard compound-wound machine.

Alternative Methods

Speed control of D.C. motors can be accomplished in three ways, of which two only are in common use. These are (1) by providing double windings on the armature; (2) by varying the voltage applied to the armature terminals; and (3) by varying the strength of the magnetic field.

The first is rarely used, and then only for special purposes, so for the present will be ignored. Method (2) may range from a simple means to the highly efficient Ward-Leonard system, to be described later, and in its simplest form is shown in Fig. 14, in connection with a shunt motor.

The method consists simply of a variable resistance connected in series with the armature. The armature current passing over this resistance causes a voltage drop to occur. If we assume that the motor is taking 5 A at 200 V, and that the maximum resistance is 5 ohms, then this voltage drop will be 5 × 5, or 25 V. The voltage applied to the armature will, therefore, be 200 − 25, or 175 V, although the full mains voltage is still applied to the field coils.

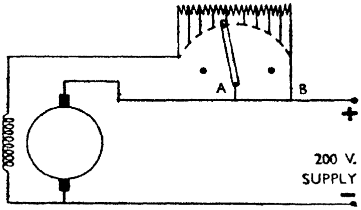


Fig. 15. Speed regulation of a shunt-wound motor by means of a resistance in the shunt circuit. If normal speed is assumed with contact arm in centre of resistance, cutting out resistance will reduce speed and inserting more resistance will increase speed. Note pivoting position (*A*). Extra connection at (*B*) ensures that circuit through the shunt regulator will not be broken in the event of faulty contact arising.

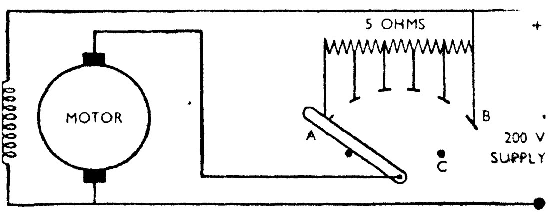


Fig. 14. Speed regulation of a shunt-wound motor by means of a resistance connected in the armature circuit. Stops are placed at (C) to prevent movable contact arm from breaking circuit, whilst (A) and (B) indicate minimum and maximum positions.

A reduction in voltage applied to the armature results in a loss of power, and consequently a drop in speed. If the full drop in voltage mentioned above, 25 V, is too great, a portion of the resistance can be cut out by means of the movable contact arm, and some smaller drop subtracted from the mains voltage.

Assuming that the resistance is graded in five steps of 1 ohm each, it will be clear that each contact represents a voltage drop of 5 V with 5 A passing over it. It is not quite as simple as this, however, as obviously the current passing varies in accordance with the load.

This method is wasteful. Considerable power is dissipated in resistance, appearing in the form of heat. Also, it is only possible to *reduce* speed from normal by this means, and it cannot be used to *increase* speed above normal. For these reasons its application is limited to special cases, but the method will be studied in greater detail later in connection with starting gear for D.C. motors.

Output Control

In the case of the D.C. generator it was found that a simple method of controlling the e.m.f. and current output from the machine was to vary the strength of the magnetic field. In the same way, a very efficient means for controlling the speed of a motor is provided by a similar device, known as a shunt regulator, connected in the shunt field as for the generator. This is indicated in Fig. 15, again in connection with a shunt-wound motor.

Assuming that the motor is under steady load, its speed will not vary if its field strength is constant. If a resistance be inserted in series with the shunt field winding, however, the exciting current will be reduced and, as a consequence, the field strength. In order to generate the required back e.m.f. the armature has no option, therefore, but to increase its speed, and this it will do.

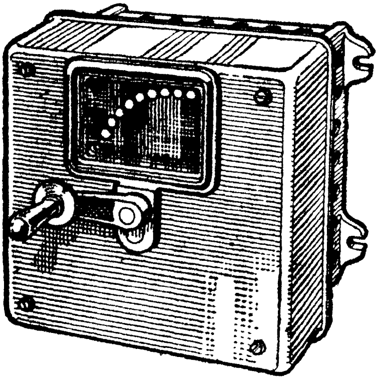


Fig. 16. Standard shunt regulator, which is ventilated at the back in order to allow for the dissipation of heat.

Conversely, if resistance be taken out of the shunt field circuit, and a larger current be permitted to flow, the flux from the poles is increased. The result is that, unless the armature slows up a bit, the back e.m.f. would exceed the applied mains voltage. With a stronger field, therefore, the speed of rotation falls, with the output of power about the same as before.

Regulator Adjustment

In practice, the shunt field regulator is usually kept to the centre contacts, representing a field excitation something below saturation point for the iron or steel used in the construction of the magnetic system. If a higher motor speed is required, some of the resistance in circuit is cut in, and with a weakened field the armature speeds up. If a lower speed is necessary, resistance is cut out, and with the stronger field the armature speed is reduced.

The same type of regulator that has been described for the generator can be used for a motor, but an alternative pattern is seen in Fig. 16.

Automatic Controllers

Automatic speed control can be arranged if necessary with the shunt regulator operated by pressure valves or other means. The more complicated automatic voltage controllers used with generators are of the same type, and operate in the last resort by means of resistance in the shunt field circuit.

Series-wound motors are controlled for speed by series resistances only, as they have no shunt field windings; a simple form of series-wound motor speed controller is seen in Fig. 17, although in some cases a field *shunt* is arranged. As this is only of special application, however, it will not be further considered here.

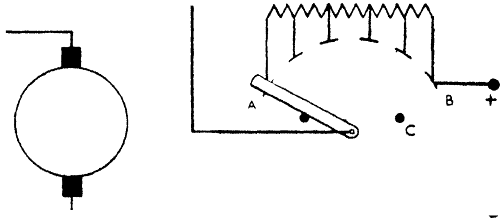


Fig. 17. Usual method of regulating speed of a series-wound motor is to use a series resistance. Resistance wires are of heavy section, as they must carry the whole current to motor without overheating.

Now let us turn for a moment to the relationship of electrical input to a motor to its mechanical output.

The text-books say that 746 W represent 1 h.p., but this is subject to modification in practice. The watt is the product of volts and amperes. One h.p. can be either 7·46 A at 100 V, or 3·73 A at 200 V. The motor described above, which was operating with 5 A at 200 V, would be absorbing 200 × 5, or 1000 W, about 1¼ h.p.

Mechanical Output

This figure of 746 W per h.p. takes no account of efficiency or of other relevant matters. Although the mechanical output of a motor is a very high proportion of the electrical input, yet there are bound to be some losses, as in the case of the generator.

Losses are caused by such things as brush friction, heating in coils, bearing friction, and windage of ventilation, and altogether amount to some 5 or 6 per cent of the energy input.

It would appear practical to allow about 800 W to produce 1 h.p. at the motor shaft, but even this takes no account of the inefficiency of drives, whether belt or gearing, and other losses associated with the circuit wiring to the motor.

The prudent engineer, in estimating requirements for a factory or a particular drive, will often allow 1000 W, or 1 kW, for every horse-power that he hopes eventually to deliver to the driven machines.

Much depends, of course, upon the types of enclosure of the motors, whether totally enclosed or of more open type; in general, drives by means of one large motor are more efficient than those employing many small ones, although the latter method has become very popular.

For simple calculations in connection with starting gear later in this chapter, it will be assumed that 5 A at 200 V, and 2 A at 500 V, represent the consumption of a 1-h.p. motor. This will not be very far from practical allowances and permits the use of simple numbers.

Direction of Rotation

Next, how do we determine the direction in which a motor armature will rotate?

The direction in which a conductor in a magnetic field moves depends upon two factors, the direction of magnetic flux and the direction of current.

In the diagram of the simple motor, Fig. 1, if the direction of current be changed, then the direction of the rotation will be reversed. This, however, is because the field system is provided by permanent magnets. In the case of the shunt-, series- and compound-wound motors, reversal of the current flow to the motor as a whole will not cause reversal of rotation, for the simple reason that both field flux direction *and* that of the current in the armature conductors are affected. With the reversal of both, the motor continues to run in the same direction as before.

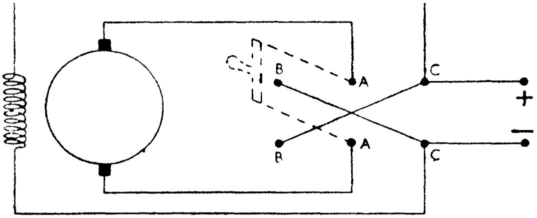


Fig. 18. Simple reversing switch for shunt-wound motor. Double-pole switch is pivoted in two contacts at (*AA*). When blades are swung over to contact with (*BB*), motor runs in one direction; when changed over to (*CC*), direction of rotation is reversed.

To reverse direction, therefore, it is necessary to reverse the direction of current flow round the field coils *or* through the armature conductors, but not both. In most commercial applications it is usual to reverse the direction of current to the armature, leaving the field undisturbed.

This is advisable, as the commutating, or interpoles, must be reversed with the direction of rotation, and it will be remembered that, as in the case of the D.C. generator, the interpole circuit is treated as one with the armature circuit. The less control gear there is in the field circuit the better, as any interruption of the shunt field is as undesirable in the case of motors as it is with generators.

A simple reversing switch, with connections, is suggested in Fig. 18, although modifications in this are necessary if the motor is to be reversed under load.

Universal Motors

It might be thought that any D.C. motor would run equally well on an A.C. supply, as the reversal of current direction would apply to both field and armature, and the motor would continue to run in the same direction. This is not the case, however.

The reader of later chapters will find that a factor known as reactance comes into play with alternating currents, and this has a serious effect upon the action of a D.C. motor. It may be said, in passing, that when A.C. is fed to an ordinary shunt-wound D.C. motor, the current through the field coils lags a long way behind the current through the armature, and neither current is at maximum at the right time for the full development of power.

An inefficient type of motor with series windings is, however, employed for small powers, usually some fraction of a h.p., as required in domestic and similar apparatus.

The ordinary vacuum cleaner is an instance of the application of a universal motor, but even so this will usually be found to develop more power on D.C. supplies than on A.C. The wide variation in the humming note of the vacuum cleaner under different conditions of load reflects the characteristic of the series-wound motor, that of considerable variation of speed between light and full load.

Universal motors of the domestic type are usually 2-pole, with one series coil placed on each side of the armature. This is shown in Fig. 19, in its simplest form. In some cases it will be found that different terminals are used for D.C. and A.C. The A.C. terminals usually short out a few turns of the field winding in order to reduce the effect of reactance.

Commutation

It is not intended to examine the problems of commutation in D.C. motors in detail, as these are identical with those of the generator, and are overcome in the same way.

If anything, however, the commutation of motors requires more careful design of the interpole circuit than with generators, as the latter are usually required to run in one direction only. The motor, on the other hand, must have perfect commutation when running in either direction, even under the very onerous conditions imposed with reversal of rotation under heavy load at steady speed. As in the case of the generator, the necessary conditions for good commutation are secured by means of interpoles, which provide the special field for the armature conductors undergoing reversal. In motors it is usual to find four interpoles, as seen in Fig. 20; the connections of these four interpoles remain as in Fig. 11, Chapter 5, except that there are now four coils in series instead of two.

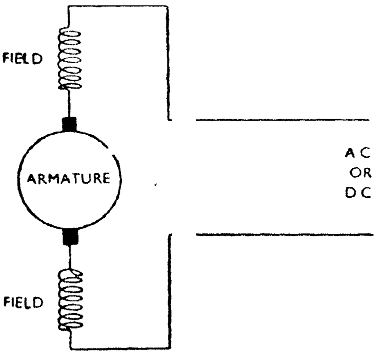


Fig. 19. Connections of a universal type motor for use on A.C. or D.C.

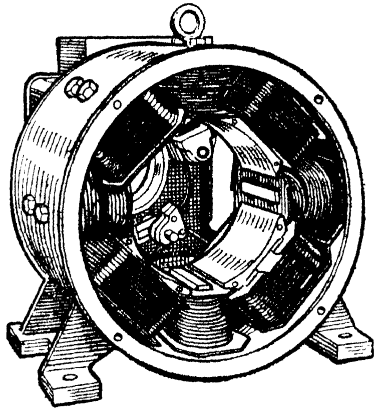


Fig. 20. Four-pole shunt-wound motor with four interpoles. Note bracing for interpoles inserted between main poles.

In the generator the polarity of the interpole is the same as that of the main pole immediately in *front* of it, in the direction of rotation; but in the motor the polarity of the interpole is that of the main pole immediately *behind* it, also in the direction of rotation.

Reversal of Current

It is clear that any reversal of current to the armature, in order to obtain reversal of rotation, must also reverse the interpole polarity. As stated above, this is one reason why the armature circuit is selected for reversal instead of the field circuit; in any motor without interpoles it is immaterial.

We are now in a position to consider methods of starting D.C. motors.

The resistance of the armature windings of a D.C. motor of anything above about 1 h.p. is of necessity very low, amounting to no more than a fraction of an ohm. In view of the fact that motors are required to operate on mains voltages, it will be seen that without some form of starting equipment the rush of current through the windings would be excessive and would easily be sufficient to destroy the windings.

Starting Switches

When the motor has run up to speed, however, the back e.m.f. keeps the armature current to the value necessary for the development of its rated power. It is only during the starting and accelerating period that precautions must be taken to choke back the armature current to a reasonable value. This is done by means of what are known as starting switches.

The simplest form is that used with the series-wound motor. The resistance of the armature and field windings combined on this type of machine would not exceed, say, ·5 ohm. If it were switched straight on to the supply without starting equipment, the current rush through the motor would be 200/·5, or 400 A.

Essential Resistance

It is necessary to provide a means for cutting down the current to some reasonable value, not more than full load current, in this case 10 A. For this purpose the low resistance of the machine windings may be ignored, and we shall find that a resistance of 200/10, or 20 ohms, placed in the line will afford this protection. It also ensures that at starting the motor receives no more than 10 A.

As the armature commences to revolve, the production of back e.m.f. begins. This opposes the mains voltage and current through the resistance and the current falls lower than 10 A. The motor will refuse to accelerate further, and will remain running slowly.

It is necessary to cut out some of the resistance, and this is done by a movable contact arm; in fact, all the resistance is cut out progressively as the armature runs up to speed. When full speed is reached the motor is safely connected direct to the main supply, without any resistance in circuit. This is, of course, a very

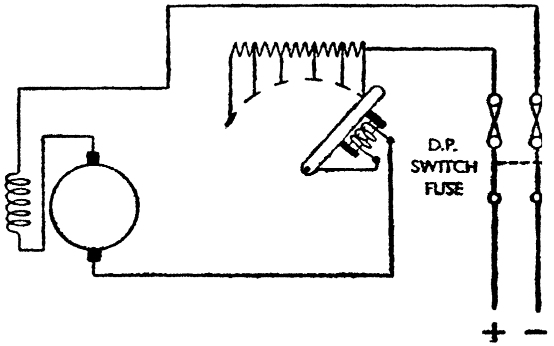
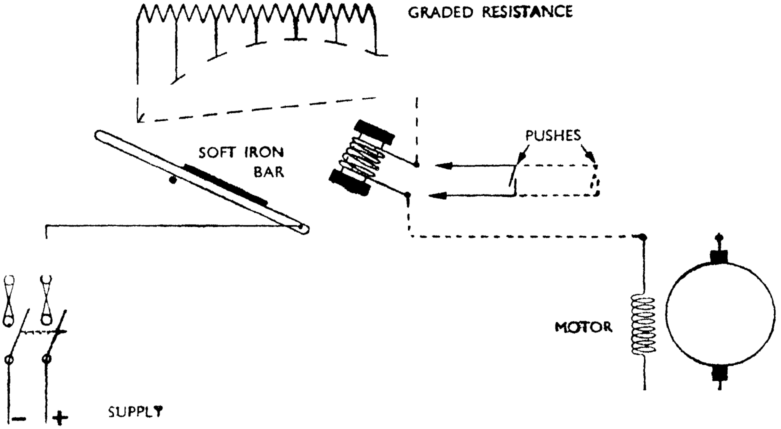


Fig. 21. Starting switch with "hold-on" or "no-volt" magnet. This magnet retains contact arm in running position against pull of a spring on its spindle; motor is stopped by opening D.P. switch fuse.



STARTER FOR SHUNT-WOUND MOTOR

Fig. 22. Graded resistance is used in the armature circuit only; full mains voltage is applied to the field circuit at starting. The "hold-on" coil is energized by the shunt circuit, whilst the special soft-iron bar is fixed on the contact arm to obtain a firm grip on the "hold-on" magnet. The pushes operate by short-circuiting the "hold-on" coil windings, and thus allowing the starting lever to return to the "off" position under the pull of the spring on its spindle.

simple device, and cannot be left in this primitive form for commercial application. For instance, suppose our motor has been safely started by means of the adjustable resistance, and then, for some reason or other, the main supply is interrupted. The motor stops and the arm remains on the last contact, cutting out all the resistance.

Modification Required

When the supply is restored there is a risk that the motor will be subjected to the full mains voltage without any starting resistance, and serious accidents to machines and operatives might occur.

It is necessary to modify the starting switch so that the contact arm is controlled by a spring, tending to return it to the starting position. It must be held in the running position by means of an electro-magnet, energized by the current passing. In the event of any failure of current, this "hold-on" coil loses its magnetism, with the result that the contact arm automatically returns to the starting position under the effect of the spring on the spindle.

The "hold-on" coil is also known as the "no-volt" coil, which indicates that with the loss of the main supply volts the switch automatically places itself in the starting position. The motor cannot be restarted inadvertently, but requires the presence of the attendant.

Switch Fuse

This modified form of starting switch is given in Fig. 21; a double-pole switch fuse will be noted, and this is standard equipment for all motor starting gear. In addition to providing an overload protective device, the switch fuse is used to stop the motor; it also permits isolation of the starting switch for adjustments or repairs.

The simple series resistance cannot be employed for any type of motor except the series-wound; with this gear a shunt-wound motor would refuse to start at all, or only move very slowly. The reason will be clear when it is remembered that the effect of the resistance is to reduce the voltage at the motor terminals; the passage of 10 A over 20 ohms means that practically all the mains voltage is absorbed, and there would be nothing to cause any current to flow round the high-resistance shunt field coils.

Switch Essentials

For shunt-wound motors, therefore, a different form of starting switch is necessary, one which, while choking back the current through the armature windings, permits the full mains voltage to be applied to the field coils, so that a strong magnetic field is at once available for starting.

The type of starting switch to be described is used for both shunt- and compound-wound motors, in the same form, for the starting conditions are identical. In the compound-wound motor the series windings are more or less incidental, in order to provide maximum field under very heavy loads; the shunt field is the important one.

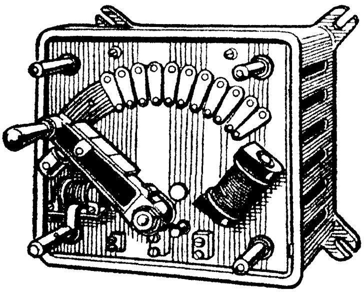


Fig. 23. Standard starter for D.C. motor. The "hold-on" coil is on the right, and the overload trip on the left.

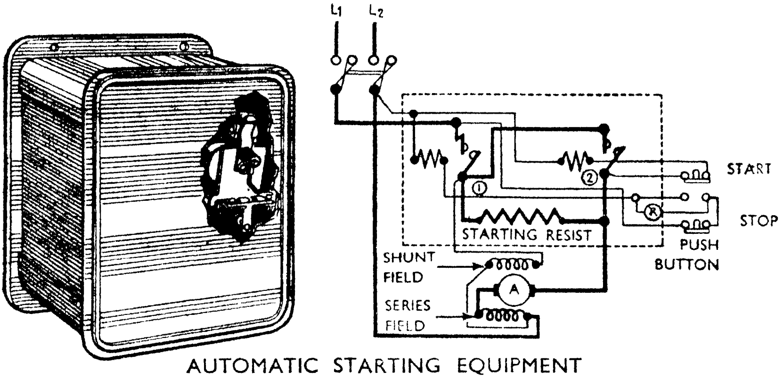
Connections of a starter for shunt-wound motors are indicated in their simplest form in Fig. 22. It will be noted that the graded resistance for use with the armature is retained, as in the case of the series-wound motor, but the "hold-on," or "no-volt," coil is now energized by the current passing to the field coils.

This is to ensure that in the event of any interruption of the supply to the field circuit, in addition to any possible mains supply failure, the starting switch immediately returns to the "start" position. A double safeguard is, therefore, provided, and both motor and operator protected against serious failure either in the vulnerable field circuit or from other causes.

Another modification will be noted, in that the connection to the field coils is taken to the *commencement* of the armature resistance; this is not haphazard, but has a definite purpose, as will be seen. When the contact arm makes contact with the first stud the full mains voltage is applied to the field coils, but the current to the armature is strictly controlled by the resistance in circuit.

As the armature runs up to speed, the arm is progressively moved over the studs, until the adjustable resistance is all cut out in the *armature* circuit, but inserted in the *field* circuit.

The reason for this is that, at starting, maximum field strength is necessary, and the field coils are energized by a current rather higher than would be necessary to



AUTOMATIC STARTING EQUIPMENT

Fig. 24. Automatic starter, operated by push buttons, for use in motors up to 5 h.p., showing contactor contacts on left, and connections on right. (1) Is the line contactor; (2) running contactor; (R) small resistance; and (A) motor armature.

maintain a correct field strength. When the motor is safely run up to speed, however, this high current is reduced; the slightly weaker field permits the correct armature speed to be maintained, and the field current reduction prevents undue heating of the field coils.

Both operations, reducing current to the armature at starting, and reducing current to the field for running, are therefore achieved by means of the one adjustable resistance.

The circuit seen on the right of the "no-volt" coil in Fig. 22 shows how emergency "stop" pushes, usually mounted near the operator on any driven machine, may be connected. The operation of the push short-circuits the "no-volt" coil, which thereupon loses its magnetism, with the result that the starting arm returns to the off position, and the motor stops.

Parallel Connection

If necessary, many of these stop pushes may be connected in parallel, and the operation of any one of them effectively stops the motor. "Limit" switches, restricting the travel of any driven machine, may be connected in the same way.

The commercial form of starting switch for shunt- or compound-wound motors is drawn in Fig. 23

Additions to devices so far described are an "overload" trip mounted in the bottom left-hand corner, and means of speed control by a shunt regulator.

Overload Trip

The former is merely a coil round which the whole of the current to the armature passes. If for any reason this is excessive, an iron lever lifts and makes contact with two studs. These studs are connected to the "no-volt" coil so that when they are short-circuited the starting lever falls back to the starting position.

The function of the overload trip is to protect the motor against excessive loads. It tends to operate if the starting lever is moved over too quickly. The proper starting of a D.C. motor takes some little time, depending on the load, and if hurried the contact studs may be burned; it will be noted that in

Fig. 23 these studs are shown as renewable.

Starting equipment is often made automatic and operated by means of push buttons located near the driven machine. A simple pattern for use with motors up to 5 h.p. is illustrated in Fig. 24, and its operation is as follows.

Push-button Starting

When the "start" button is pressed, the line contactor closes and the motor armature is connected to the main supply through the starting resistance. At the same time, the operating coil circuit of the second contactor is connected across the motor armature, and as the motor accelerates to full speed the armature voltage gradually increases until it reaches sufficient value to close the second contactor.

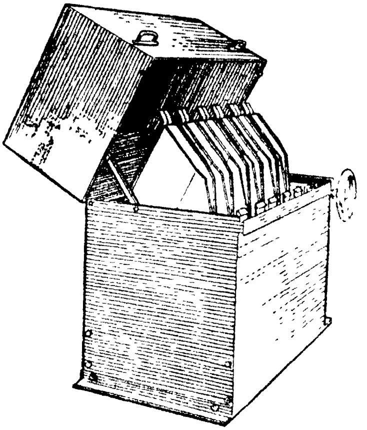
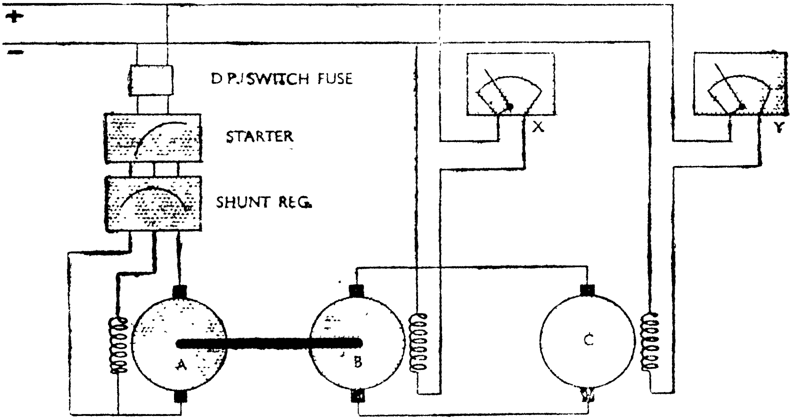
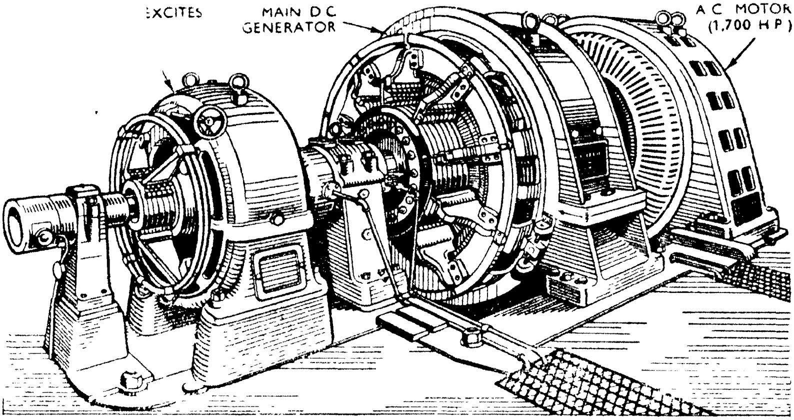


Fig. 25. Starter gear in which liquid is used for resistance instead of wire coils. Short-circuiting contacts are shown on the front of the plates. This type of liquid starter gear is preferred by some engineers, especially for large motors, to avoid a jerky action.



WARD-LEONARD SYSTEM OF SPEED CONTROL

Fig. 26. (*A*) Driving motor; (*B*) generator driven by (*A*) and on same shaft; (*C*) is the motor to be controlled, and which is driving machine. Starting procedure would be: all resistance of shunt regulator (*Y*) is cut out, giving maximum excitation for the motor (*C*); all resistance is inserted in shunt regulator (*X*), which causes (*B*) to deliver approximately full-load current to motor (*C*) when the latter is stationary; motor (*C*) then starts against full load, and, as its speed and back e.m.f. rises, resistance is cut out of (*X*) so as to maintain full-load current; the resistance in shunt regulator (*Y*) is then inserted until maximum speed of motor (*C*) is reached. This is the ideal method for regulating speed of D.C. motors.



CONTROLLING A LARGE HOIST MOTOR

Fig. 27. G.E.C. Ward-Leonard set used in mines; output of generator is 1200 kW.

When this occurs the starting resistance is cut out and the motor is connected direct to the mains with full voltage across the armature. Contactors are, of course, switches operated by means of electromagnets, and "no-volt" protection is afforded by the fact that if the mains supply fails, then the circuit to the contactors is interrupted, and the switches open.

Although the construction and principle of the starting switch are similar to those of the speed regulator, yet starting gear should not be used for speed regulation purposes. The resistance coils are rated to carry maximum current for a matter of minutes only, and if speed regulation is required, this must be separately applied.

With tapped resistances, current is fed to the armature in a series of jerks. For this reason, some engineers prefer to use liquid resistances, especially for large motors. In these, metal electrodes are slowly lowered into a semi-conducting liquid; when a small area of the electrode has entered the solution the resistance is comparatively high, but as larger areas make contact, the resistance is reduced.

The action is very smooth, and one form is illustrated in Fig. 25, the plates being lowered by means of the handwheel on the right. When the plates are fully immersed, metal contacts complete the circuit, and these may be clearly seen on the front of the plates and the inner edge of the case.

The ideal method of regulating the speed of direct-current motors under heavy load is afforded by the Ward-Leonard system (Fig. 26). In this the motor is driven by the current from a motor generator—a generator driven by means of an electric motor—and the driving motor may be either A.C. or D.C. In Fig. 26 the driving motor is a D.C. machine, and is shown with its starting and speed control gear on the left.

Mounted on the same shaft is the generator *B*, with its field excited from the mains supply; there is a shunt regulator in circuit. The output from the generator is fed directly into the motor armature *C*, which is the machine doing the work and which has to be regulated for speed. The field of this motor is also directly excited from the D.C. main supply, also with a shunt regulator in circuit.

Efficient Speed Control

In spite of the fact that a rather larger output machine must be used for the motor generator, and that three machines are required instead of one, speed control by the Ward-Leonard system is remarkably efficient. Control is exercised from very slow to maximum speeds entirely by field control, and if the motor *C* is to be reversed in addition, then the shunt regulator *X*, controlling the generator *B*, is made of the potentiometer reversing type, so that the input to the armature of *C* is reversed. Control may be made automatic, but the arrangement is too complicated to be illustrated here, and in any case varies according to requirements.

A Ward-Leonard set for controlling a large hoist motor is shown in Fig. 27, the output of the generator being 1200 kW. The method is widely used for cage hoists in mines, where very close speed control is necessary.

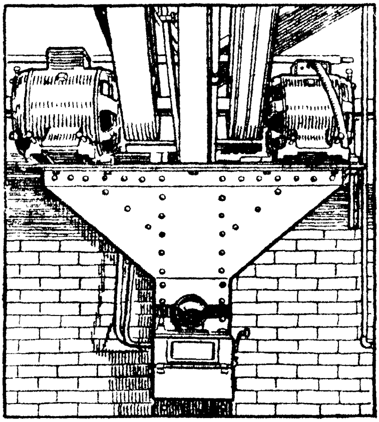


Fig. 28. Two motors of 20 h.p. and 12½ h.p. arranged for flat belt drive.

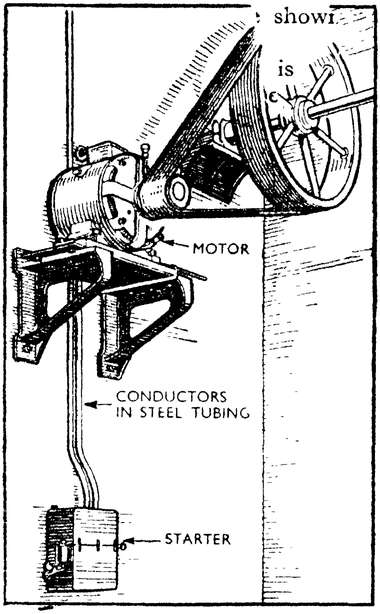


Fig. 29. 15-h.p. motor with multiple V-belt drive. Note short distance between driving and driven shafts.

A modification of the Ward-Leonard system is known as the Ward - Leonard - Ilgner system, which uses a smaller motor generator with the addition of a heavy flywheel. This means that when the motor is at times called upon to work above its rating, that is, with some overload, then the energy stored in the flywheel is given up and normal speed maintained.

When an Ilgner system is driven by means of an A.C. motor a further refinement in the form of a "slip-regulator" may be employed, providing additional control.

A great advantage of the electric motor is that its small size for

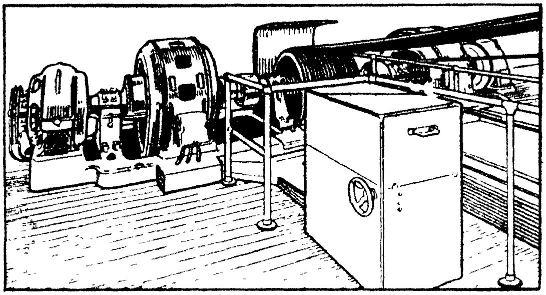


Fig. 31. Coupled motors driving through multiple ropes working in grooved pulleys. With the liquid controller, a fine adjustment of speed is possible.

com[illegible]ely large po[illegible]output permi[illegible] to be mounted in positions where other forms of prime mover would be unsuitable. In Fig. 28 the motors are mounted on the top of a stanchion, and the drive effected by flat leather belts. Where the distance between the motor and the driven machine is long, this provides a very useful method of drive.

When distances between the machines are necessarily short, then driving by multiple V pulleys and endless V belts is usually adopted. An example is seen in Fig. 29, and it will be noted that the distance between the driving and driven shafts does not appear to exceed about 4 ft. Driving by flat belts under these conditions would be very unsatisfactory, owing to the small area of grip for the flat belt on the driving pulley of the motor, and the only alternative to the V belts would be a chain.

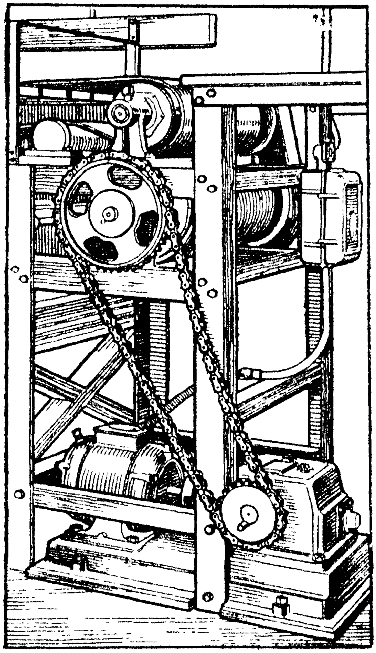


Fig. 30. Chain drive, through reduction gearing, from a 3-h.p. motor.

Chain Drives

A chain drive is seen in Fig. 30 and in addition there is a speed-reduction gear box driven directly from the motor shaft. The versatility of drives adaptable to the electric motor are almost without limit and many different forms may have to be adopted in the same works; this will be realized when it is stated that the three drives in Figs. 28, 29, and 30 are in the same factory.

A further example from the same factory is given in Fig. 31, where the main drive is by means of two motors mechanically coupled together. The liquid controller will be noted in the foreground. In this main drive, however, the power is transmitted by means of multiple ropes working in grooved pulleys.

CHAPTER 7

ALTERNATING-CURRENT EFFECTS

NATURE OF A.C. SINE WAVE. FREQUENCY. VECTORS. R.M.S. VALUES. EFFECTS OF RESISTANCE AND INDUCTANCE. PHASE DIFFERENCE. REACTANCE. EFFECTS OF CAPACITANCE. REACTANCE OF A CONDENSER. COMPARISON OF INDUCTIVE AND CAPACITIVE EFFECTS. ALTERNATING-CURRENT CIRCUITS. ADDING VECTORS OUT OF PHASE. RESISTANCE AND INDUCTANCE IN SERIES. IMPEDANCE TRIANGLE. ANGLE OF LAG. GENERAL SERIES CIRCUIT. POWER AND POWER FACTOR. EXAMPLES OF CIRCUIT CALCULATION. POWER FACTOR IMPROVEMENT.

NEARLY all the electricity we use in our homes and in our factories is in the form of alternating current. In fact, almost the whole of the vast amount of electrical energy used in all parts of the world for every imaginable purpose is produced by alternating-current generators, called alternators.

This might lead any one to suppose that alternating current (A.C.) must be better than direct current (D.C.) for all general purposes. But this is not really the case. Actually, there are many purposes for which D.C. is essential, examples being the charging of batteries, electro-plating, and the production of aluminium and copper by electrical means.

Need for High Voltages

Even for these purposes the necessary direct current is nowadays usually derived from an A.C. supply by the use of suitable converters or rectifiers.

For lighting and heating, A.C. and D.C. are equally useful.

There are several reasons why alternating currents are used so widely. Most important is the fact that where large amounts of power are concerned high voltage is necessary. We know that power is represented by the product of voltage and current, so that if the voltage were low, say, for example, 230 V, which is generally used for lighting, the current output from a large generating station would be literally hundreds of thousands of amperes.

High-voltage Generation

One can imagine the enormous size of conductors that would be required to carry such currents. The design of generators, cables and transmission lines would be quite impossible in such circumstances.

The difficulty is met by generating at moderately high voltage, say 11,000 V or more. A high-voltage A.C. generator is much simpler and cheaper than a D.C. generator of the same size, as no commutator is required and the armature winding can be carried on the stationary part of the machine.

Then, again, the alternating current supply has the all-important

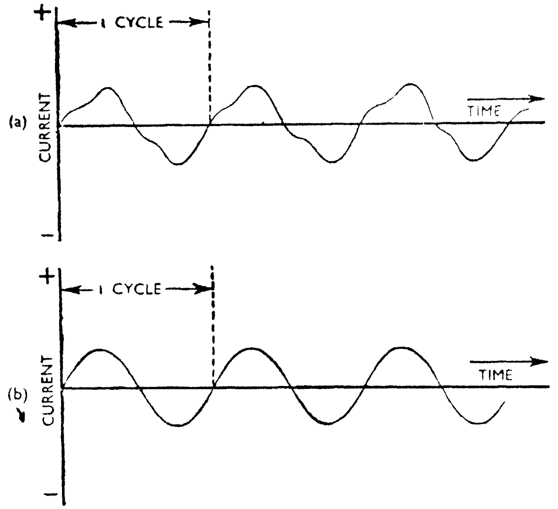


Fig. 1. Alternating-current waves. At (a) is shown an irregular wave-form, but each cycle of current is an exact replica of the previous one. Alternating e.m.f.'s and currents produced by machines usually have both positive and negative half-waves the same shape, as shown here. (b) A sine wave of A.C. This is the simplest possible wave-form, and alternators are designed to give as nearly as possible a sine wave of e.m.f.

advantage that voltage given by the generator can be stepped up to a higher value still by means of transformers, making it possible to use transmission lines with reasonably small conductors. At the receiving or consumer's end of the line the voltage can be just as easily stepped down again to the low values supplied to the ordinary consumer.

Let us consider in a simple way what an alternating current is and see if we can find out some of its more important properties. As the name implies, an alternating current is one which flows backwards and forwards in a conductor or circuit, the direction of flow being reversed at regular intervals.

The current rises from zero value to a maximum or peak value in one direction, then begins to decrease again, falling to zero and building up to the peak value in the reverse direction, after which it again falls to zero. The sequence is repeated over and over again.

Choosing Direction

One way round the circuit is taken as positive and the other negative. It does not matter, as a rule, which of the two directions is chosen as the positive one.

If a graph is plotted showing how the current varies from instant to instant, the curve obtained is in the form of a series of waves. The idea is illustrated in Fig. 1, where current is plotted against time.

Irregular Waves

The first curve is irregular in form, but successive waves are of exactly the same shape. Irregular waves do sometimes occur in practice, but alternators are designed to produce e.m.f.'s with as simple and regular a wave-form as possible. Such a wave is illustrated in Fig. 1b and is called a *sine wave*, about which we shall have more to say presently. Fortunately, in power work irregular waves are the exception rather than the rule, and sine waves are much more easily dealt with both in theory and in practice.

A glance at the curves of Fig. 1 shows that they are centrally placed about the zero line or time base; there is as much negative current as there is positive. Thus the average or mean value of the current taken over one complete wave is zero.

This does not necessarily mean that no power is given. Power depends on both current and voltage, and if the voltage reverses at the same time as the current, power is given during each half wave. The question of power is dealt with more fully further on.

Cycles and Frequency

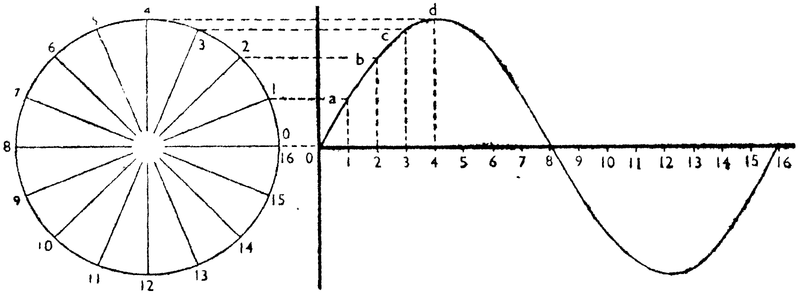
One complete sequence or succession of positive and negative values, that is, one complete wave, is called *one cycle*, as indicated in Fig. 1, and the number of cycles occurring every second is the *frequency* of the current, expressed in cycles per second.

The standard frequency for power supply in this country is 50 cycles per second (50~) and in the U.S.A. it is 60~. When the frequency is stated to be 50 cycles, as is common, this re[illegible] showi[illegible]ans 50 cycles per second. Anc[illegible] ne for frequency is *periodic*[illegible] is referring to the number of periods per second, where one period is the time in seconds of one cycle.

Before discussing the nature of a sine wave, let us first see what is meant by one ampere of alternating current, or of one volt of alternating e.m.f., whatever the wave-form might be. When purchasing an electric-light bulb or an electric fire it is not necessary to state whether it is to be used on A.C. or D.C. supply. It is only necessary to state the voltage and the "wattage."

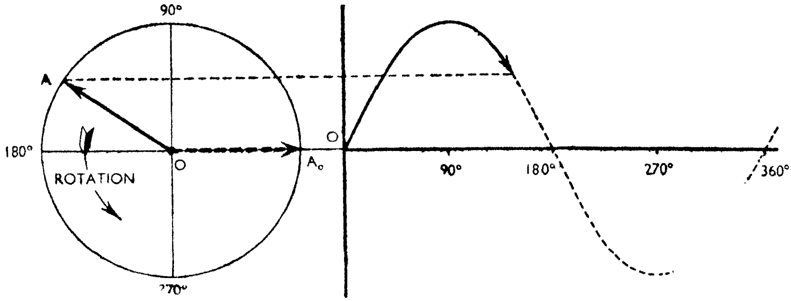
The electric fire gives the same amount of heat per hour whether it is operated from A.C. or D.C. supply of the "same voltage," and a suitable ammeter will show the "same value" of current in each case; and yet the alternating voltage and current are varying all the time between upper limits in opposite directions. The voltmeter and ammeter give steady readings as though they were in a D.C. circuit.

All this means that the apparent or virtual values of alternating voltage and current, as indicated



SIMPLE METHOD OF DRAWING A SINE WAVE

Fig. 2. Both the circle and the base on which the sine wave is to be drawn are divided into sixteen equal divisions and numbered. The points where horizontal and vertical lines from corresponding numbers meet give points such as *a*, *b*, *c*, etc. When a smooth curve is drawn through these points the sine wave is produced.



REPRESENTATION OF THE ANGLE OF ROTATION

Fig. 3. Line *OA* rotating about the end *O* enables one to visualize the tracing out of a complete sine wave during one revolution of *OA*. Each revolution gives one full wave or one cycle. The base line of one complete wave corresponds to 360 deg.

by the voltmeter and ammeter, are really the values of the equivalent direct voltage and current which would produce the same amount of heat in a given time in the same resistance (in this case the resistance of the electric-fire element).

So we may define the *effective value* of an alternating current as the value of the steady direct current which would produce the same amount of heat every second as the alternating current, in a given constant resistance. This obviously means that the *average power* of the alternating current is equal to the power of the equivalent direct current.

So if I amperes is the effective value (that is, the value of the equivalent D.C.) in a resistance of R ohms, the *average* power is $P = I^2R$ watts.

This is derived from Ohm's Law as follows:

$P = EI$, but $E = IR$, therefore $P = I^2R$.

But the current and power are actually varying from instant to instant. If i is the current at any instant, the power at that time is i^2R watts. The average or mean power is, therefore, equal to the mean value of i^2R. So we can write,

$$I^2R = \text{mean value of } i^2R,$$

$$\text{or } I^2 = \text{mean value of } i^2, \text{ if } R \text{ equals 1 ohm.}$$

Then, taking the square root of each side gives the effective value,

$$I = \sqrt{\text{mean value of } i^2}.$$

This is a very important conclusion. In words it means that the effective value is, quite irrespective of wave-form, equal to the square root of the mean of the squares of all the instantaneous values. This is usually called the "Root Mean Square," or R.M.S. value.

Sine Waves

In practice, the term "R.M.S. value" is much more widely used than "effective value," and now we see how the term originated.

By similar reasoning it can be shown that the effective value of an alternating *voltage* of any wave-form is equal to the Root Mean Square value.

The sine wave is so important in A.C. work that we cannot make much headway without knowing something about it. And, strange as it may seem, this very knowledge will enable us to replace sine waves in our reasoning and calculations by straight lines, called vectors. We shall be using such vectors later on.

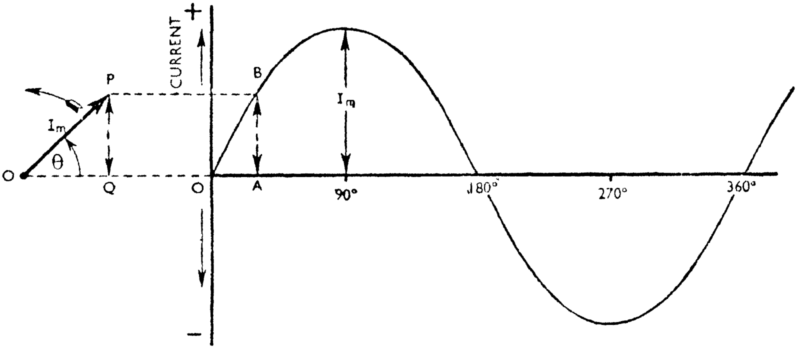
First of all, let us see how a sine wave can be drawn in a simple manner by the aid of a circle. On the left of Fig. 2 a circle is divided into a number of equal parts; in this case, sixteen for convenience. On a line drawn horizontally through the centre of the circle, sixteen divisions are marked off and numbered to the right from a starting point *O*. For the moment the length of each division does not matter, provided they are all equal.

Drawing a Vector

Now, from division 1 on the circle, a horizontal (dotted) line is drawn to meet, at *a*, the vertical line through division 1 on the straight line base. Doing the same thing for division 2 on both circle and base-line we get meeting-point *b*. Going step by step right round the circle in this way we get a series of points, *a*, *b*, *c*, *d*, etc., and on drawing a smooth curve through these points we have our sine wave.

Suppose that instead of taking only sixteen points we imagine the circle to be divided into a very large number of very small divisions. The points *a*, *b*, *c*, *d*, etc., would then be so close together that they themselves would form the sine wave.

Following this idea further, suppose that we have a straight line *OA*, as in Fig. 3, and imagine that it starts rotating in the anti-clockwise direction from the horizontal position *OA* about the end *O*. As the end *A* moves along the circle we can imagine the corresponding sine wave to be traced in the right-hand part of the diagram. When *OA* has made exactly one revolution, that is, when it has turned through 360 deg., one complete sine wave will have been traced out. So the base of the



SINE WAVE OF ALTERNATING CURRENT

Fig. 4. This diagram shows how a sine wave of A.C. can be fully represented by a rotating vector *OP*. The length of *OP* is equal to the peak value I_m of the current to some scale, and *OP* rotates anti-clockwise with constant r.p.s. equal to *f*, where *f* is the frequency of the current. The base line of the sine wave is divided to represent angular rotation of the vector from the horizontal position *OQ*. The current *i* at the instant concerned is given by the sine wave at *AB* and by the vector at *QP*. It is more useful to plot the current against angular rotation of the corresponding vector than directly against time. The angle passed through is proportional to time, the shape of the curve being unchanged.

sine wave can be divided to represent the angle of rotation of *OA* at various stages, as illustrated.

We see, then, that a sine wave can be produced from a rotating straight line or *vector* of constant length, and that the maximum height of the sine wave is equal to the length of the vector. We say that the vector represents the sine wave.

So, a sine wave of alternating current, as illustrated in Fig. 4, can be represented, and eventually replaced, by a vector *OP* rotating about the end *O* in the anti-clockwise direction. The length of *OP* is made equal to the maximum value I_m of the current, to the same scale as in the sine wave, for instance, 1 in. = 10 A.

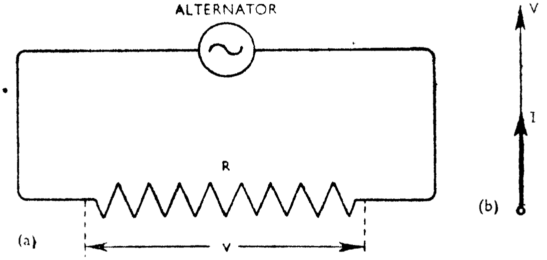


Fig. 5. (a) Simplest A.C. circuit, a resistance *R* connected across the terminals of an alternator. (b) Vectors representing R.M.S. values of voltage and current. It is a good plan to represent currents by heavy-line vectors with broad arrow-heads, and voltages by thin-line vectors with pointed arrow-heads. The direction of current when positive, that is, during a positive half-wave, may be taken either way. There is no phase difference between voltage and current in a circuit having only resistance and the vectors are in line as shown above and in Fig. 6.

Time and Angular Rotation

Distances along the base of the sine wave represent time as well as angular rotation of the vector, which, therefore, rotates with constant speed; that is, equal angles in equal times. One revolution of the vector gives one cycle of current, and so, if the frequency is *f* cycles per second, the speed of the rotating vector is *f* revolutions per second.

The angle θ between the vector and the horizontal line is called the *phase* of the current at the instant concerned. At this instant the current has a value i, given at *AB* by the sine wave and at *PQ* by the vector. So if we wish to know the value of i at any point in the cycle, we can find it just as well from the vector as from the sine wave itself.

For any wave-form of current or voltage, except a rectangular wave, the effective value is less than the peak or maximum value. In the case of a sine wave, which has regular form, it can be shown that the effective or R.M.S. value is $\frac{1}{\sqrt{2}}$, or 0·707 times the peak value. So if I_m is the peak value of a sine wave of A.C., the R.M.S. value is $I = 0{\cdot}707\, I_m$.

This means that if the peak value is, say, 10 A in either direction, the effective value, or the equivalent direct current with the same heating effect, is 7·07 A.

R.M.S. Value

Whenever we refer to the "strength" of an alternating current, or the "value" of an alternating voltage, we mean the R.M.S. value, as indicated by ammeter or voltmeter. As the R.M.S. value is an exact fraction of the peak value, we can use vectors to represent R.M.S.

values, instead of maximum values, for most purposes. This greatly simplifies A.C. circuit calculations and problems, and the use of vectors will be illustrated after we have considered the separate effects of resistance, inductance and capacitance in A.C. circuits.

Applying Ohm's Law

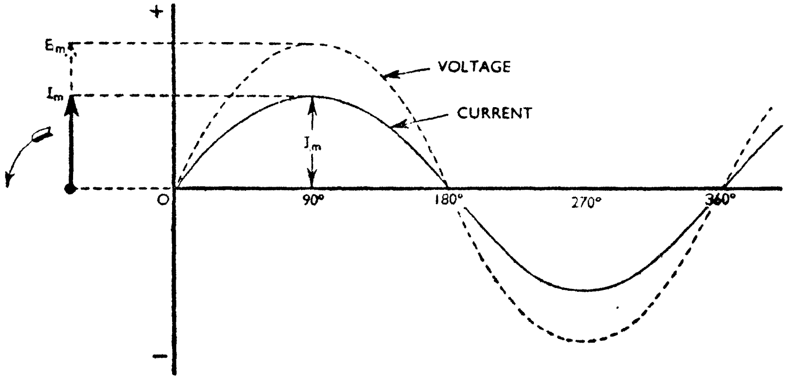
In dealing with steady direct current we use Ohm's Law to find the current in a resistance when a voltage is applied. For instance, if a steady voltage, V, is applied to a coil of resistance R ohms, the current builds up to a steady value, $I = V/R$ amperes. The coil may have inductance, but although it delays the building up of direct current it has no effect whatever on the final value reached.

In A.C. circuits, however, inductance (the property described in Chapter 3) and *capacitance*, which will be explained in a moment, have most important effects which have to be taken into account. There are many instances in practice where these effects are so great that resistance plays a comparatively unimportant part, or even a negligible part. So where inductance or capacitance is present, Ohm's Law, as we know it, cannot be used. We shall see that only in the particular case where the circuit contains nothing but resistance can Ohm's Law be applied.

Let us then take this simplest case first. For purposes of explanation, we can regard a straight piece of resistance wire as having neither inductance nor capacitance. If such a resistor R is put across the terminals of an alternator as in Fig. 5, the current is at every instant equal to the voltage divided by the resistance, because there is no induced or other e.m.f. within the resistor to upset the Ohm's Law equation, $i = e/R$.

The reader will observe that the small letters i and e are used to represent instantaneous values.

When the voltage reaches its maximum value the current will also be greatest, and when the voltage passes through zero the current does likewise. This means that the voltage and current waves are exactly *in step*; they are said to



VOLTAGE AND CURRENT IN PHASE

Fig. 6. Vectors are drawn in position for the instant of maximum voltage and current. The waves are exactly in step, there being no phase difference.

be *in phase* with each other and are represented by the sine waves of Fig.6.

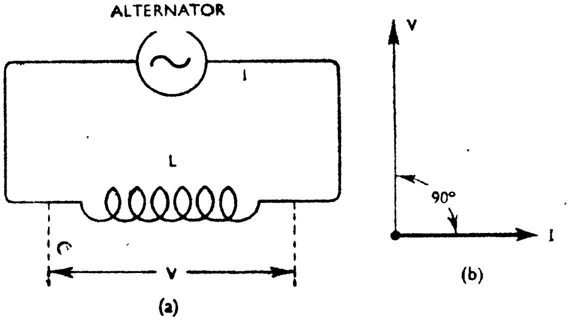


Fig. 7. Coil *L* is assumed to have no resistance. The flow of A.C. is opposed by the self-induced e.m.f. caused by the changing of the current from instant to instant. The voltage and current waves are a quarter of a cycle out of step and the corresponding vectors are at right angles, as explained in the text with the aid of Fig. 8. For a given applied R.M.S. voltage *V*, the R.M.S. current is $I = V/2\pi fL$ amps, lagging 90 deg. behind the voltage.

On the left of the diagram the corresponding voltage and current vectors are drawn for the instant of maximum voltage and current. Since these maximum values occur together, the vectors are in line with each other; there is no phase angle between them. At the instant of maximum voltage E_m, the maximum current is $I_m = E_m/R$ amperes. Then, multiplying each side by 0·707 converts the maximum voltage and current into R.M.S. values V and I, giving $I = V/R$ amperes.

So, for a simple resistance, Ohm's Law is true for R.M.S. values and, in addition, *the voltage and current waves and vectors are in phase*. We can use all the same rules here as for a resistance in a D.C. circuit, namely,

$$\text{Current, } I = \frac{V}{R} \text{ amperes}$$

$$\text{Voltage, } V = IR \text{ volts}$$

$$\text{Resistance, } R = \frac{V}{I} \text{ ohms}$$

$$\text{Power, } P = I^2R \text{ watts}$$

$$= VI \text{ watts}$$

$$= \frac{V^2}{R} \text{ watts.}$$

The vectors for R.M.S. values of V and I are shown in Fig. 5b.

Electric lamps, fires, kettles, irons and all heating devices can be treated as simple resistances, the amount of inductance present being too small to have any influence.

Any coil or circuit in which a current produces lines of magnetic force has the property of self-induction, that is, the property of inducing an e.m.f. in itself *whenever the current is changing*.

An alternating current is changing all the time, except for an instant at each peak value when it ceases to rise and begins to fall again. So when A.C. is driven through an inductive coil, an e.m.f. is induced inside the coil and completely upsets Ohm's Law.

Introducing Inductance

Now let us see what actually happens when the results are completely contrary to Ohm's Law. Suppose, for example, a coil of inductance L henrys is connected to an alternator, as you will find illustrated in Fig. 7. If the alternator gives out a sine wave of voltage, the resulting current will also be a sine wave of the same frequency. What we have to find out is the value of R.M.S. voltage V that will be required to produce any given R.M.S. current I, or vice versa.

Let us consider what we have already been told about self-induced e.m.f. Up to the present there are two very important points. The first is that its value e^1 in volts is equal to the inductance L in henrys multiplied by the *rate at which the current is changing* in amperes per second, that is,

$e^1 = L \times$ (rate of change of current).

The *value* of the current at the instant concerned does not matter in the least.

The second is that the induced e.m.f. always acts in such a direction that it tries to prevent the change of current actually causing it, and so *opposes* the action of the applied voltage (Lenz's Law).

Nett e.m.f.

If, then, the applied voltage is e and the induced (back) e.m.f. is e^1, the resultant or nett e.m.f. acting on the resistance is $e - e^1$, and we must modify the Ohm's Law equation to suit the new conditions, thus,

$$i = \frac{e-e^1}{R} \text{ amperes,}$$

from which $e = iR + e^1$ volts.

In words, this means that in driving the current i through the coil, the applied voltage e has to overcome both the opposing resistance and the self-induced or back e.m.f. The term iR is the back pressure due to the passage of the current through the resistance and e^1 is the back e.m.f. of self-induction.

In the first place, let us imagine that we have somehow managed to wind a coil having no resistance, but only inductance L henrys; then, in the last expression, $R = 0$, and, therefore, $e = e^1$. This means that instead of the applied e.m.f. being countered or balanced by both iR and e^1, it is balanced by e^1 only. So when only inductance is present, the applied voltage is exactly countered or balanced by the induced e.m.f. at every instant.

Let us make quite sure that we appreciate this point, and that we do not raise the false argument that *some* difference must exist between the applied voltage and the back e.m.f. to drive the current through the coil. No driving is necessary where there is no opposition or resistance. A ball rolling along a perfectly smooth level surface in a vacuum needs no force to keep it in motion; no e.m.f. is required to keep a current flowing in a *resistanceless* conductor.

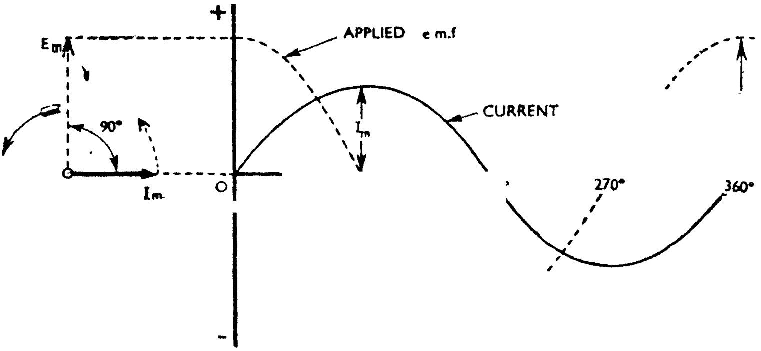
But if the velocity of the ball is changing, the necessary applied force must be exactly equal and opposite to the opposing force of inertia (mass × rate of change of velocity). In the same way, when the current is changing, the applied voltage must be equal and opposite to the opposing induced e.m.f. (inductance × rate of change of current). Actually, the current must change at exactly the right rate to give an induced e.m.f. equal and opposite to any applied e.m.f., if there is no resistance. The electrical and mechanical laws are alike and inductance is often referred to as "electrical inertia," that which opposes change of current.

The electrical balance is, perhaps, more easily seen if we write the last equation in the form,

$$e - e^1 = iR \text{ volts.}$$

Here $e - e^1$ is the nett or resultant e.m.f. acting on the resistance R. When $R = 0$, there is no voltage required to pass the current through and $e - e^1 = 0$, or $e = e^1$.

Now let us consider a sine wave of current flowing through the coil of inductance L. This current is represented by the full-line curve of Fig. 8. At the instant of maximum value it is neither increasing nor decreasing; its rate of change is zero. Therefore, at this instant the induced e.m.f. is zero, and so is the applied voltage if there is no resistance. So we discover, perhaps with surprise, that the current is greatest when the voltage is zero, and vice versa. This means that the voltage and current waves are exactly a quarter of a cycle out of step, as in Fig. 8.



PHASE DIFFERENCE OF NINETY DEGREES

Fig. 8. Waves are a quarter of a cycle, or 90 deg. out of step, and the corresponding vectors are drawn in position for the maximum positive voltage and zero current. The voltage leads the current by 90 deg. or the current lags by 90 deg. behind the voltage. Vectors out of phase by a quarter of a cycle are said to be *in quadrature*.

Here, again, there may be a little difficulty in seeing what is happening, and an analogy might be helpful. The action can be likened to that of a weight suspended on a spring and set into vertical oscillation. The weight comes to rest at the bottom of the stroke, where the pull of the spring is greatest, and moves with its greatest velocity at the middle of the stroke, where the force on it is zero. If it is kept in mind that the current must at all times vary at such a rate as to induce an e.m.f. equal and opposite to the applied e.m.f., and that the actual value of the current plays no part, the action is not difficult to follow.

In Fig. 8 the current is rising from zero to the maximum *positive* value during the first quarter of a cycle from 0 to 90 deg., and therefore the applied voltage, shown by the dotted-line curve, must be *positive* during the whole of this time. It is greatest at the beginning, just as the current starts to rise from zero.

The current and voltage vectors are shown on the left of the diagram for the instant of zero current and maximum positive voltage. They are at right angles and are said to have a *phase difference* of 90 deg. Since the voltage vector is in advance of the current vector, the applied voltage *leads* the current by a quarter-cycle. On the other hand, the current lags behind the applied voltage by 90 deg.

To find the peak value E_m of the voltage we must know the greatest rate at which the current changes. This occurs, of course, where the current wave in Fig. 8 is steepest, that is, as it passes through zero. At this instant the current vector is horizontal, and the *vertical* speed of its tip gives the maximum rate of rise of current.

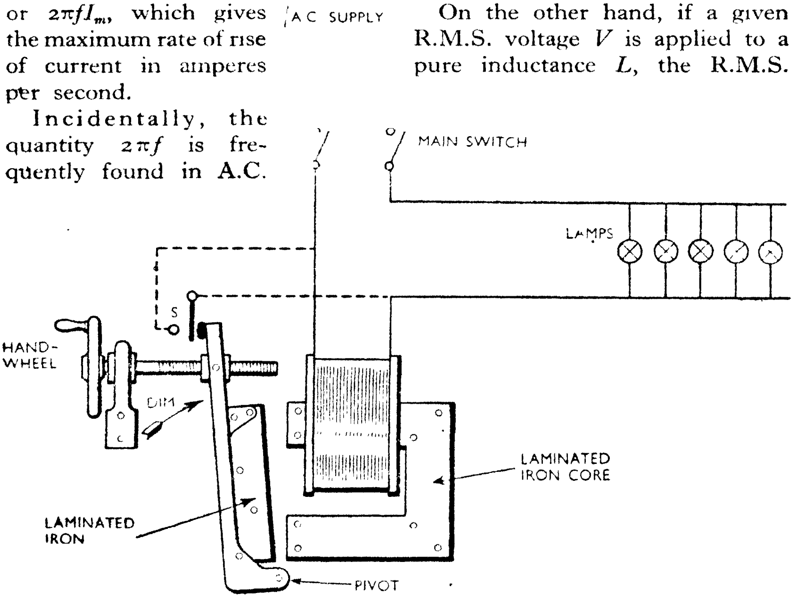
Now, the end of the vector moves round a circle of radius I_m, making f revolutions per second, where f is the frequency of the current. But the circumference is 2π times the radius, where $\pi = 3{\cdot}1416$, and therefore the speed of the tip of the vector is $2\pi I_m \times f$, or $2\pi f I_m$, which gives the maximum rate of rise of current in amperes per second.

Incidentally, the quantity $2\pi f$ is frequently found in A.C. formulæ and is often replaced by the symbol ω and is known as the angular frequency or pulsatance. It is actually the angular velocity of the rotating vector representing the current or voltage. But to get back to the point, how does this back e.m.f. affect the current?

Since e.m.f. $=$ L $\times$ (rate of change of current), the maximum voltage is $E_m = L \times 2\pi f I_m$, or $E_m = I_m \times 2\pi f L$ volts.

Multiplying each side by 0·707, converts the maximum voltage and current into R.M.S. values V and I, giving $V = I \times 2\pi f L$. This is the voltage required to drive the current I through the inductance.

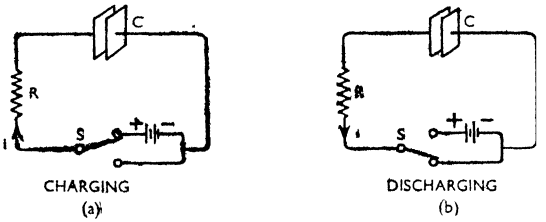
On the other hand, if a given R.M.S. voltage V is applied to a pure inductance L, the R.M.S.



CURRENT CONTROL BY MEANS OF A REACTOR

Fig. 9. Diagram to illustrate the use of a reactor of variable inductance for gradually dimming or brightening a bank of lamps, for stage use, for instance. The reactor has a variable air-gap in the magnetic circuit, the inductance and reactance being least when the armature is farthest from the core, and vice versa. The movement of the armature is controlled by a handwheel and screw-thread feed. In the l on" position the switch S short-circuits the reactor out.

current passed is $I = \frac{V}{2\pi fL}$, amperes, *lagging* 90 *deg. behind the voltage.* The vectors of R.M.S. voltage and current are given in Fig. 7.



CHARGING (a)

DISCHARGING (b)

Fig. 10. Simple circuits illustrating (a) the charging of a condenser C and (b) discharging of the condenser, through a resistance R. If the switch S is vibrated rapidly between the upper and lower contacts, alternate charging and discharging currents flow through R. This is an alternating current.

The quantity $2\pi fL$ is the number by which the voltage must be divided to give the current when no resistance is present. It is called the *reactance* of the coil, is measured in ohms (because, like resistance, it is equal to the ratio of volts to amps) and is usually denoted by the letter X.

So, for an inductance without resistance we have,

$$I = \frac{V}{X} = \frac{V}{2\pi fL} \text{ amperes,}$$

$$\text{or } V = IX \text{ volts.}$$

It must always be remembered that for a pure reactance there is a phase difference of a quarter-cycle between voltage and current.

It can be taken as a golden rule that heat can be produced by a current only where there is resistance. In fact, a resistance can be defined as that which causes heat to be evolved when current flows.

An inductance without resistance does not take any power from an A.C. supply. A glance at Fig. 8 will help us to see why this is so. During the first quarter-cycle, from 0 to 90 deg., both the voltage and current are positive, and their product, being positive, represents power input to the coil. The energy absorbed is that required to build up the magnetic field.

During the next quarter-cycle, from 90 deg. to 180 deg., when the current is now falling to zero, the current is still positive though falling, but the voltage is now reversed. The power is, therefore, *negative* during this period, meaning that the coil is giving energy back to the supply; as the magnetic field falls to zero it gives back the whole of its energy.

So the nett amount of energy taken over each half-cycle is nil, and the *average power* over any whole number of cycles is zero.

Lagging Current

We learn, then, that a current which is out of phase with respect to the voltage by a quarter-cycle gives zero average power. For this reason a current lagging behind (or leading) the voltage by 90 deg. is called a *wattless current,* or idle current.

A reactor or choke is a coil specially designed to have low resistance and comparatively high reactance, being usually wound on an iron core to give the required inductance for a minimum number of turns. A little resistance cannot, of course, be avoided.

A reactor in series with any consuming device acts as a voltage reducer or current limiter without itself consuming any appreciable power. An example of this is illustrated in Fig. 9.

The second property we have to consider in connection with A.C. is *capacitance*.

When a potential difference or voltage exists between two conducting bodies, electrostatic lines of force extend from one body to the other, that is, an electric field is produced between them (this is different from a magnetic field, which is produced by a current).

Condensers

A condenser, or capacitor, is an arrangement of two conducting layers, such as tin-foil, separated a small distance from each other by an insulating medium, such as mica, oiled paper, or air. The lines of force are condensed into the small space between the "plates," hence the name "condenser."

The special property of a condenser is that a quantity of electricity Q (= current × time) has to be imparted to one set of plates to produce a potential difference e, one being proportional to the other. If Q is in *coulombs* or ampere-seconds and e is in volts, the capacitance of the condenser is $C = Q/e$ *farads*, and so the "charge" thus becomes $Q = C \times e$ coulombs.

The behaviour of a condenser in an A.C. circuit is often surprising and certainly interesting to any one studying the effects for the first time. For instance, when we know that no current can possibly flow through a condenser from one set of plates to the other, because of the insulation between them, we may be somewhat surprised to find that a lamp can be made to light when in *series* with a condenser on an A.C. supply. It would appear as though an A.C. were flowing *through* the condenser. But this is only apparent.

When we "charge" a condenser we do not "put electricity into it," as is frequently stated. What we really do is to transfer electrons from one set of plates to the other, round the outside circuit, by applying an e.m.f. This stream of electrons is the charging current.

A simple condenser, resistance and battery circuit is shown in Fig. 10. When the switch S is pushed up, the condenser charges up, a momentary current passing through the resistance R. On changing the switch over to the lower position the condenser discharges through the resistance, where a

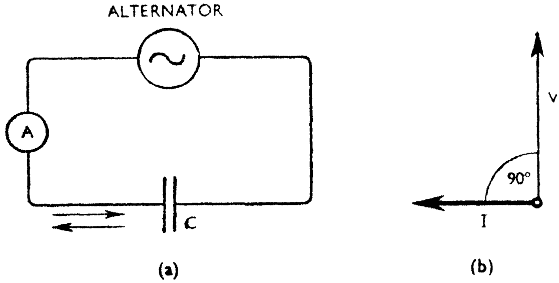
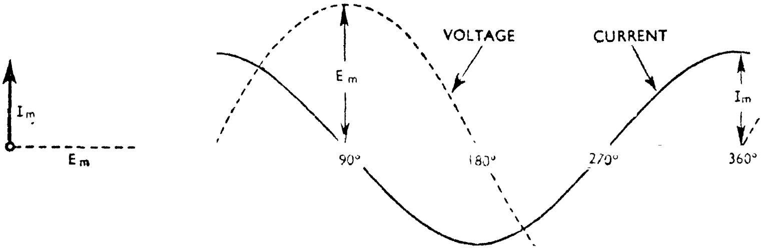


Fig. 11. Condenser C connected to an alternator through an A.C. ammeter A. The condenser is charged up first in one direction and then in the other as the alternator voltage builds up and reverses. The resulting current is alternating and is indicated by the ammeter. (b) Vector diagram of R.M.S. voltage and current. The current leads the applied voltage by 90 deg. and is given by $I = 2\pi fC \times V$, with C in farads. (1 farad = one million microfarads, or 1 microfarad = 10^{-6} farad.)



EFFECT OF CAPACITANCE IN A.C. CIRCUITS

Fig. 12. Current leads the applied voltage by a quarter-cycle and vectors are drawn in position for the instant of maximum positive current and zero voltage. $I_m = 2\pi fC \times E_m$, where $\frac{1}{2\pi fC}$ is the reactance of the condenser.

reverse momentary current now flows.

If the switch is vibrated rapidly up and down between the upper and lower contacts, alternate charging and discharging currents flow through the resistance R; in fact, we shall then find that we have an alternating current.

Alternate Charging

On replacing the battery and switch by a source of alternating voltage as shown in Fig. 11, we get a somewhat similar effect, the condenser C being charged first in one direction and then in the other as the voltage reverses. The resulting to and fro movement of electrons round the circuit connecting the plates is an alternating current, which can be measured by the ammeter A.

The rate at which the voltage between the plates of a condenser builds up is exactly proportional to the charging current; by doubling the charging current we should get twice the charge, and therefore twice the voltage, in a given time. The current is actually the rate at which the charge increases or decreases.

If C is the capacitance of the condenser, the charge at any instant is $C \times$ voltage. Therefore, the rate of change of charge, that is, the current, is given in amperes by,

$$i = C \times \text{(rate of change of voltage)},$$

where C is in *farads*.

It will be seen that this is the same kind of expression as $e = L \times$ (rate of change of current), used for inductance.

So, for a condenser all we have to do is to write voltage where we had current, current where we had voltage, and capacitance C where we had inductance L.

Current Lead

At the same time, the sine waves of voltage and current in Fig. 8 change places, and so do the vectors, as shown in Fig. 12. Whereas for inductance we had $V = I \times 2\pi fL$, for the condenser we have $I = V \times 2\pi fC$ amperes (R.M.S.), and *the current leads the voltage by a quarter-cycle.*

Since the voltage and current are 90 deg. out of phase, their ratio $\frac{V}{I}$ is a *reactance.*

Measuring Reactance

Since $I = V \times 2\pi f C, \frac{V}{I} = \frac{1}{2\pi f C}$.

You can check this by cross-multiplication. So, the reactance of a capacitance is $\frac{1}{2\pi f C}$, where f is the frequency and C is in *farads.*

It must be remembered that one microfarad (μF) is a millionth part of a farad. So in making calculations where the capacitance is *stated* in microfarads, one has to divide C by one million, or 10^6, to convert it to farads. For instance, the reactance of a 10μF condenser at 50~ is,

$$X = \frac{1}{2\pi f C} = \frac{10^6}{2\pi \times 50 \times 10} = 318 \text{ ohms.}$$

We have found that both inductance and capacitance give rise to reactance in an A.C. circuit, there being a phase difference of 90 deg. between volts and amperes in each case. But whereas a pure inductance takes a current lagging 90 deg. behind the applied voltage, a condenser takes a current leading the voltage by 90 deg. For this reason, capacitive reactance, $X_C = -\frac{1}{2\pi f C}$, must be regarded as negative with respect to inductive reactance, $X_L = 2\pi f L$, when they occur together in the same circuit.

Wattless Current

For instance, if an inductance L and a capacitance C are connected in series, the resultant or overall reactance is $X = X_L - X_C$ ohms. Like a pure inductance, a condenser takes a wattless current, the average power being zero unless the insulation is imperfect.

In A.C. circuit calculations it is often necessary to add together two or more R.M.S. currents or voltages, and here we find a very important difference between A.C. and D.C. methods, because phase difference plays an important part. If two consuming devices on the same supply point take R.M.S. currents of 2 and 3 A respectively, the total R.M.S. current is not necessarily 5 A. It depends on whether the two currents to be added are in phase with each

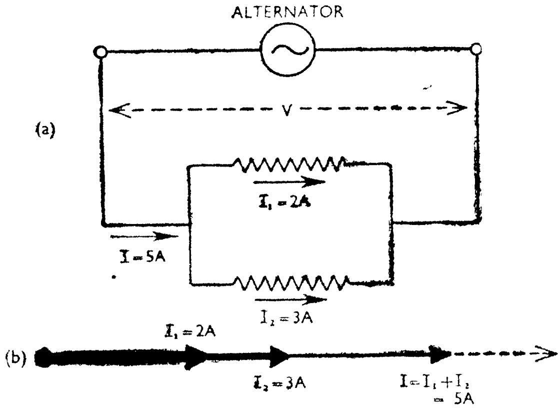


Fig. 13. (a) Two resistances in parallel connected to an A.C. supply. The branch currents I_1 and I_2 are each in phase with the supply voltage V, and, therefore, with each other. The total current I is found by direct addition of I_1 and I_2 because all vectors are in line with each other, as shown at (b). It is only when currents (or voltages) are in phase that they may be added in this way.

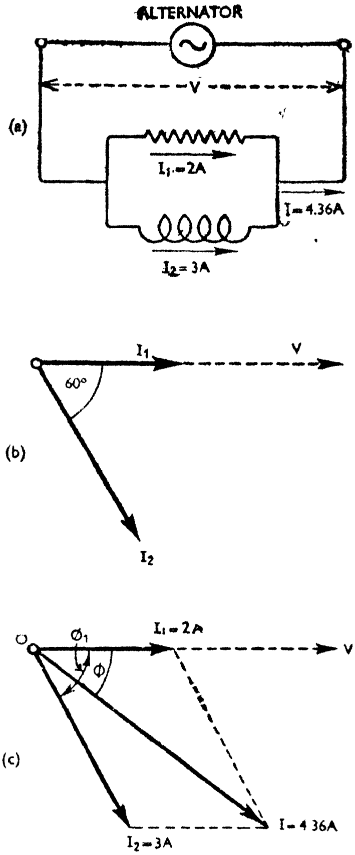


Fig. 14. (right) (a) Non-inductive resistance in parallel with a coil containing both resistance and inductance. The branch currents I_1 and I_2 are out of phase as shown by the vector diagram at (b). The total current I supplied is not equal to the direct or arithmetical sum of I_1 and I_2, but is found by the parallelogram method as shown at (c). This can be done graphically by drawing to scale and measuring the length of OI. In this case $I_1 = 2$ A in phase with the voltage and $I_2 = 3$ A assumed to lag 60 deg. behind the voltage. When the vector diagram at (c) is drawn to scale, the total current found by measuring the length of OI is just under 4·4 A. The value of I can be calculated from the expression

$$I = \sqrt{I_1^2 + I_2^2 + 2I_1I_2\cos\phi_1},$$

where ϕ_1 is the angle between the vectors to be "added." Cos 60 deg. = $\frac{1}{2}$ and the calculation gives $I = 4{\cdot}36$ A. The angle ϕ between the vector OI and the voltage vector gives the angle of lag of the resultant current. I is called the "vector sum" of I_1 and I_2.

other or not. A useful analogy is presented by the case of two forces acting upon a body. If, for instance, two forces of 2 lb. and 3 lb. act upon a body, the resultant or total effective force will depend on the directions of the individual forces. Only if they are in the same direction will the total force be 5 lb.

Each of the two resistors in Fig. 13a takes a current in phase with the supply voltage, and the currents are, therefore, in phase with each other. Here the R.M.S. currents I_1 and I_2 can be added directly to give the total current $I = I_1 + I_2 = 2 + 3 = 5$ A. This is because their peak values and the peak value of their sum all occur at the same time; all three vectors being, therefore, in line as shown at (b). It will be shown presently that a coil with both resistance and inductance takes a current lagging behind the voltage by an angle less than 90 deg. In Fig. 14a, such a coil, taking 3 A lagging 60 deg. behind the voltage, is shown in parallel with a resistor taking 2 A (in phase with the voltage).

Phase Relationship

The vector diagram at (b) shows the two currents I_1 and I_2 in their correct phase relationships to the voltage and to each other. If the vectors are drawn to scale, the total current will be found to be less than

5 A, because the separate currents will reach their peak values at different times.

Parallelogram Method

The way to find the total current is shown at (c) in Fig. 14. A parallelogram is drawn as illustrated, and the diagonal OI gives the total current I. Its length gives the value of the current and its angle with respect to the voltage vector will give the angle of lag.

Measuring OI in a diagram drawn to scale we would find $I = 4{\cdot}36$ A. On the other hand, the value can be found by calculation (*see* caption to Fig. 14).

The truth of the parallelogram method is quite easily seen. For instance, in Fig. 15a two voltages in series, and with a phase difference ϕ between them, are represented by the vectors OE_1 and OE_2. In this case the lengths correspond to peak values, the instantaneous values being e_1 and e_2 as shown (*see* Fig. 4). At this instant the total voltage is $e = e_1 + e_2$.

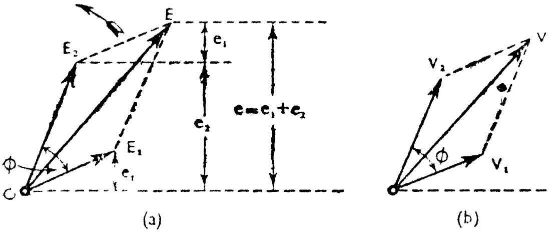


Fig. 15. (a) Diagram which graphically proves the parallelogram method of adding vectors. OE_1 and OE_2 are two voltage vectors to be added, the lengths representing peak values, and e_1 and e_2 are the instantaneous values, as shown in Fig. 4. The total instantaneous voltage is $e = e_1 + e_2$, which is the value given by the vertical line from the end of OE to the base line. So OE is the vector representing the sum of the voltages. Reducing all three vectors in the ratio of 0·707 to 1, gives the R.M.S. values as illustrated at (b), where the vectors are now stationary as time is not involved with R.M.S. values.

We can see at a glance that the vertical line from the end of the diagonal vector OE to the horizontal base line is equal to $e_1 + e_2$. Therefore, OE is the vector giving the resultant or total voltage. And what applies to peak values also applies to R.M.S. values, as already explained.

Now that we know the separate effects of resistance, inductance and capacitance we can find the effects of any two, or all three, together in the same circuit. The use of vectors simplifies matters and makes the drawing of sine waves no longer necessary for our purpose.

Electrical Equivalent

A coil of resistance R and inductance L, as represented in Fig. 16a, is electrically equivalent to a simple resistance R *in series* with a pure inductance L, as illustrated at (b). This is because the same current I generates heat in R and produces the magnetic field associated with L. We can, therefore, find separately the voltages V_1 and V_2 necessary to drive the current I through each part.

Since V_1 and V_2 are in series in the equivalent circuit, their *vector sum* gives the total voltage V across the circuit. The voltages must be added *vectorially* as already explained, if they are out of phase.

The voltage across R is $V_1 = IR$ in phase with I, and the voltage across L is $V_2 = IX$, 90 deg. in advance of I, where X is the reactance $2\pi fL$ at the frequency f. So if we draw the current vector OI as in Fig. 17a, the voltage vector V_1 is parallel to it and V_2 is 90 deg. in advance, as shown. On completing the rectangle OV_1VV_2, the diagonal vector OV gives the total voltage V.

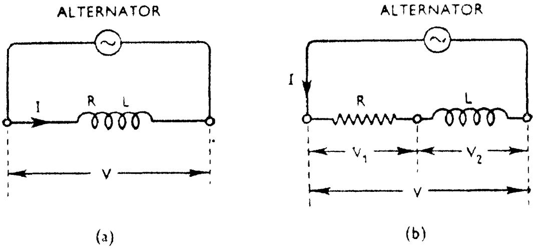


Fig. 16. (a) Coil with resistance R and inductance L connected to an A.C. supply. This is electrically equivalent to a non-inductive resistance R in series with a resistanceless coil of inductance L, as illustrated at (b). The voltages V_1 and V_2 can be calculated but not measured directly, for in the actual coil at (a) R and L are mixed up together. Vector diagrams are given in Fig. 17.

Now, the connection between the diagonal and sides of the rectangle is $V^2 = V_1^2 + V_2^2$. Then, putting $V_1 = IR$ and $V_2 = IX$ gives $V^2 = I^2R^2 + I^2X^2$, so that,

$$V = I\sqrt{R^2 + X^2} \text{ volts.}$$

The quantity $\sqrt{R^2 + X^2}$ is the number by which the current must be multiplied to give the voltage, or by which the voltage must be divided to give the current. It is called the *impedance* of the circuit, and is in ohms.

Denoting the impedance by Z, we have the following equations:

$$V = IZ \text{ volts}$$
$$I = V/Z \text{ amperes}$$
$$Z = V/I \text{ ohms}$$

in each of which $Z = \sqrt{R^2 + (2\pi fL)^2}$ ohms.

We see at once that, in the A.C. circuit, impedance Z takes the place of resistance R in the Ohm's Law equations for a D.C. circuit. The impedance is the total extent to which the A.C. is *impeded* or opposed by the combined effects of resistance and reactance.

Although we have been dealing with resistance and inductance in series in finding that impedance is equal to the ratio of applied volts to amperes, that is, $Z = V/I$ ohms, this simple definition of impedance is true for any A.C. circuit, made up of any groupings of R, L and C. It does not apply to motors and the like where a generated e.m.f. occurs due to the presence of motion.

Impedance Triangle

In the present case, with R and L in series, the impedance is $Z = \sqrt{R^2 + X^2}$ ohms, where $X = 2\pi fL$. So, in finding Z, the resistance and reactance must be "added" as though they were two vectors of lengths R and X *at right angles to each other*. In fact, the resistance, reactance and impedance can be represented by the three sides of a right-angled triangle as illustrated in Fig. 18. This is called the "impedance triangle" of the circuit and is most useful in letting one see at a glance how R, X and Z are related to each other.

If we multiply each side of the impedance triangle by the current I, we get the three voltages $V_1 = IR$, $V_2 = IX$ and $V = IZ$ given at (b) in Fig. 17.

For resistance alone there would be no phase difference between the voltage and current, whereas for inductance alone the current would lag by 90 deg. behind the applied voltage. So with both resistance and inductance present we should expect to find the current lagging by some angle less than 90 deg. behind the applied voltage. This is actually so, as is shown in Fig. 17.

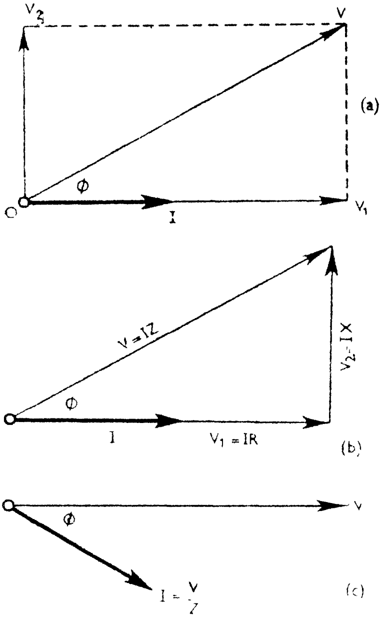


Fig. 17. (a) Vector diagram of the inductive resistance of Fig. 16. The applied voltage V is made up of two "components": $V_1 = IR$ in phase with the current I, and $V_2 = IX$ leading I by 90 deg., where $X = 2\pi fL$ ohms. V_1 is the part of the applied voltage required to drive the current through the resistance, and V_2 is the part required to overcome the reactive e.m.f. due to self-induction. The vector diagram can be drawn in a somewhat simpler form as at (b), which leads to the impedance triangle of Fig. 18 (c) For a given applied voltage V, the resulting current has a value $I = V/Z$ amps, where $Z = \sqrt{R^2 + (2\pi fL)^2}$, and the current lags behind the voltage by the angle ϕ, where $\cos\phi = R/Z$.

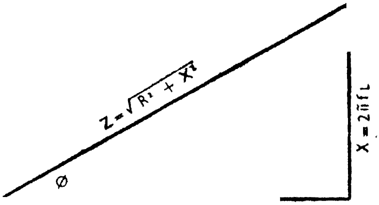


Fig. 18. Impedance triangle, showing the relationship between R, X and Z, namely, $Z = \sqrt{R^2 + X^2}$. The phase angle ϕ of the circuit is also indicated. $\cos\phi = R/Z$, or $\tan\phi = X/R$. Compare the impedance triangle with the voltage triangle of Fig. 17b.

The current is seen to lag behind the applied voltage V by the angle denoted by ϕ (this is a Greek letter pronounced "phi" or "fie").

This same angle ϕ is given in the impedance triangle of Fig. 18 between the sides R and Z. The ratio R/Z is called the *cosine* of the angle ϕ, written $\cos\phi$. It is a number less than 1 (unless $\phi = 0$, when $\cos\phi = 1$), and it plays a very important part in the calculation of power in A.C. circuits.

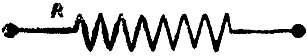
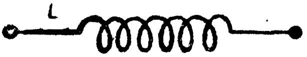
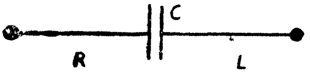
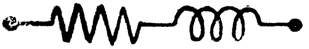
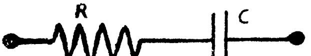
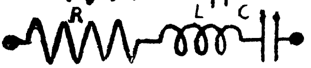
What we have just done for R and L in series applies in general to any series circuit. For instance, with resistance and capacitance in series the impedance is again $Z = \sqrt{R^2 + X^2}$ ohms, but in this case the reactance is $X = \frac{1}{2\pi fC}$ ohms, and the current in the circuit leads the applied voltage by the angle ϕ, where $\cos\phi = R/Z$.

The circuit is shown in Fig. 19 and the corresponding vector diagrams in Fig. 20.

The most general case is that with R, L and C in series. The combined reactance of L and C is then $2\pi fL - \frac{1}{2\pi fC}$ ohms, so the general impedance formula is,

$$Z = \sqrt{R^2 + (2\pi fL - \tfrac{1}{2\pi fC})^2}\,\text{ohms}.$$

With voltage V applied to the circuit the current is $I = V/Z$

Circuit	*Impedance (Z)*	*Power Factor (cos φ)*
	R	1
	$2\pi fL$	0 lagging
	$\frac{1}{2\pi fC}$	0 leading
	$\sqrt{R^2 + (2\pi fL)^2}$	$\frac{R}{Z}$ lagging
	$\sqrt{R^2 + \left(\frac{1}{2\pi fC}\right)^2}$	$\frac{R}{Z}$ leading
	$\sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}$	$\frac{R}{Z}$ lagging or leading

amperes, and the phase difference ϕ between the voltage and the current is again given by $\cos\phi = R/Z$. If $2\pi fL$ is greater than $1/2\pi fC$, the inductive reactance preponderates and the current lags by the angle ϕ, whereas if $1/2\pi fC$ is greater than $2\pi fL$, the current leads.

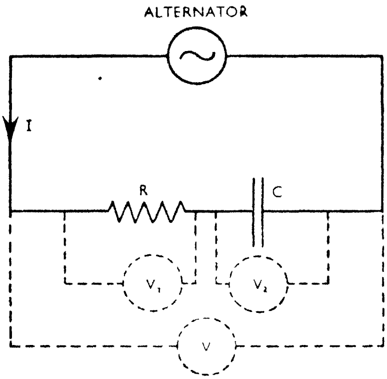


Fig. 19. Resistance R and capacitance C in series. In this case R and C are separate and the voltages V_1 and V_2 can be actually measured. $V_1 = IR$ in phase with I, and $V_2 = I/2\pi fC$ lagging by 90 deg. In terms of the total applied voltage V, the current is $I = V/Z$ amps., where $Z = \sqrt{R^2 + (1/2\pi fC)^2}$ ohms. The current leads the voltage by an angle ϕ, where $\cos\phi = R/Z$. The vector diagrams and the impedance triangle are given in Fig. 20.

For the convenience of the reader the impedances and power factors (discussed further on) of the various circuits so far considered are collected together in the above table.

It will be noted that both resistance and reactance, when they occur alone, are given as impedances. This is quite true, for if we examine the general impedance formula, $Z = V/I = \sqrt{R^2 + X^2}$, we see that for a simple resistance (for which $X = 0$) the impedance is $Z = \sqrt{R^2 + 0} = \sqrt{R^2} = R$. Similarly, for reactance alone $Z = \sqrt{0 + X^2} = X$. In fact, a resistance alone is an impedance of zero phase angle, and a reactance alone is an impedance of 90 deg. phase angle.

In a D.C. circuit the power in watts is equal to the product of volts and amperes. In an A.C. circuit, too, the power *at any instant* is equal to the product of

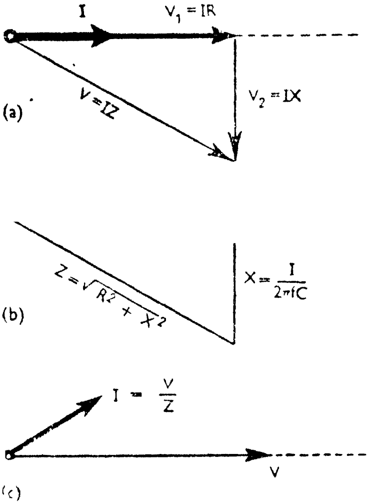


Fig. 20. (a) Complete vector diagram for the circuit of Fig. 19. The voltage V_1 across the resistance R is in phase with the current I, whereas the voltage V_2 across the condenser lags by 90 deg. The condenser current is 90 deg. in advance of V_2 across the condenser. The total voltage V is the vector sum of V_1 and V_2. (b) The impedance tri-

angle derived directly from the voltage vectors. (c) For a given applied voltage V the current is $I = V/Z$ amps, where Z is the total impedance of the circuit. The angle of lead of the current is

[illegible]

voltage and current *at that instant*. But in most practical work we want to know the *average power* in terms of R.M.S. volts and amperes, the values indicated by measuring instruments.

Here we find another important difference between A.C. and D.C. methods, for the average power in an A.C. circuit is not necessarily equal to the product of R.M.S. voltage and current; it depends upon whether there is any phase difference or not between the voltage and the current. We have seen that the average power in a resistance R carrying an alternating current is $P = I^2R$ watts, where I is the effective or R.M.S. current. In fact, the definition of effective value was based on this.

It will be remembered that heat is generated only where there is resistance, and that reactance takes zero average power. So, if we consider an inductive resistance such as the coil of Fig. 16a, the whole of the power consumed is still $P = I^2R$ watts.

As the voltage is not involved in this expression, the question of phase difference does not arise.

Now we can write the power equation $P = I^2R$ in the form $P = I \times I \times R$ watts. If Z is the impedance of the coil, $I = V/Z$ amperes, where V is the applied R.M.S. voltage. Substituting this for one of the I's in the power equation gives $P = \frac{V}{Z} \times I \times R$, or $P = VI \times \frac{R}{Z}$ watts.

As seen from the impedance triangle, of Fig. 18, Z is greater

$Z = \sqrt{R^2 + X^2}$; and so R/Z is less than 1.

The average power is, therefore,

amperes and volts for a circuit where there is a phase difference ϕ between voltage and current. We have seen that $R/Z = \cos \phi$, and it is usual to express the average power in the form $P = VI \cos \phi$ watts.

So to get the power in an A.C. circuit we have to multiply the product VI, called the volt-amperes, by the factor $\cos \phi$. This is called the *power factor* of the circuit and is the number by which the volt-amperes must be multiplied to give the true average power.

The power factor (P.F.) of any circuit is defined as the ratio

$$\frac{\textit{watts}}{\textit{R.M.S. volts} \times \textit{R.M.S. amps.}},$$

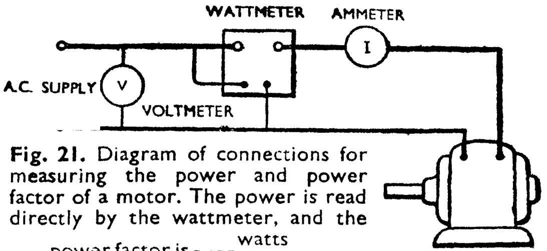


Fig. 21. Diagram of connections for measuring the power and power factor of a motor. The power is read directly by the wattmeter, and the power factor is $= \frac{\text{watts}}{\text{volts} \times \text{amps}}$.

and is only equal to cos ϕ with sine waves of voltage and current.

In the case of a simple resistance there is no phase angle and cos $\phi = 1$, giving $P = VI$, as already seen. So the P.F. of a non-inductive or non-reactive load is unity.

In power work we use the larger units: 1 kilowatt (kW) = 1000 watts, and 1 kilovolt-ampere (kVA) = 1000 volt-amperes. Then,

$$\text{kW} = \text{kVA} \cos\phi.$$

The power factor of a circuit can never be greater than 1 and is positive whether the current is lagging or leading. When the current lags behind or leads the voltage by an angle ϕ, the power factor is stated as cos ϕ lagging or cos ϕ leading, as the case may be (*see* table on page 155).

We are faced with the fact that we cannot find the power in an A.C. circuit from ammeter and voltmeter readings unless we know the phase difference. If we can calculate the value of cos ϕ, well and good, but very often we cannot. In these circumstances we must measure the power directly with a wattmeter, an instrument which automatically takes the power factor into account.

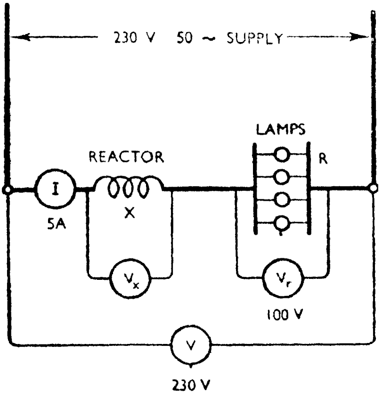


Fig. 22. Circuit in which a reactor *X* is put in series with a bank of lamps to dim them. The advantage of using a reactor rather than a resistor is that the former consumes very little power in comparison with the latter.

A wattmeter has a current coil, connected in series with one line like an ammeter, and a volt coil connected between the lines, like a voltmeter. The phase difference between the currents in the two coils is equal to the phase angle of the "load" and affects the reading in such a way as to take the power factor into account.

Motor Efficiency

The connections of wattmeter, voltmeter and ammeter for measuring the power and power factor of a motor are shown in Fig. 21. The power P is given directly by the wattmeter. If V and I are the readings of the voltmeter and ammeter, the power factor of the motor is $\cos\phi = \frac{P}{V \times I}$.

We have now gained sufficient knowledge to make quite a variety of useful calculations. Let us make a power factor calculation on a motor first.

A 1·5 h.p. motor on a 230-V single-phase supply is found to take 8·15 A and 1500 W at full load. It is required to find the power factor and efficiency of the motor.

The power factor is $\cos \phi = \frac{\text{watts}}{\text{volts} \times \text{amps}} = \frac{1500}{230 \times 8{\cdot}15} = 0{\cdot}8.$ The output from the motor, since 1 h.p. = 746 W, is $1{\cdot}5 \times 746 = 1119$ W.

$$\text{Efficiency} = \frac{\text{power output}}{\text{power input}} =$$

$$= 0{\cdot}746, \text{ or efficiency} = 74{\cdot}6$$

per cent.

Next let us find the details of a coil from the measured values of volts, amperes and watts. An inductive coil when connected to a 100-V 50~ supply consumes 300 W, the current being 5 A. It is required to find the impedance, resistance, reactance and inductance of the coil.

The impedance is $Z = \frac{V}{I} = \frac{100}{5} = 20$ ohms.

The power consumed is

$$P = I^2R \text{ watts}$$

$$300 = 5^2R,$$

or resistance,

$$R = \frac{300}{5^2} = \frac{300}{25} = 12 \text{ ohms.}$$

Now, $Z = \sqrt{R^2 + X^2}$, or

$$Z^2 = R^2 + X^2$$

$$20^2 = 12^2 + X^2$$

$$X^2 = 20^2 - 12^2 = 256.$$

Therefore, reactance $X = \sqrt{256} = 16$ ohms.

NOTE: Square roots are most easily found from mathematical tables, which can be bought for a few pence from any technical bookseller. Also, another very easy method, although, of course, not absolutely accurate, is by using a slide rule.

We find the inductance from the expression $X = 2\pi fL$, that is, inductance $L = \frac{X}{2\pi f} = 16$ $= 0{\cdot}051$ henry.

Now let us try a more elaborate one (Fig. 22). A bank of 230-V lamps used for stage lighting is to be dimmed by means of a reactor in series. The practical arrangement is shown in Fig. 9.

The supply voltage is 230 and it is required to reduce the voltage at the lamp terminals to 100, the current taken by the lamps at this voltage being 5 A (found by preliminary test).

We want to find what value of series reactance will be necessary to give these conditions and what is the power factor of the circuit. The resistance of the reactor may be neglected.

The lamps are non-inductive, the

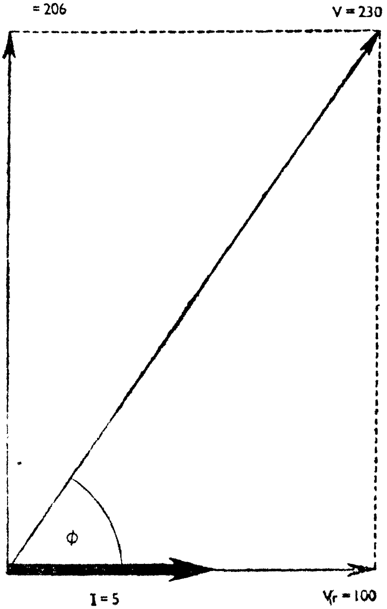


Fig. 23. Vector diagram for the circuit of Fig. 22. The voltage V_x across the reactor is shown 90 deg. out of phase with the current because the reactor is assumed to have negligible resistance.

resistance at the reduced voltage being $R = \frac{100}{5} = 20$ ohms. The complete circuit takes 5 A from the 230-V supply, and the circuit impedance is, therefore, $Z = \frac{V}{I} = \frac{230}{5} = 46$ ohms. If X is the reactance of the reactor,

$$Z = \sqrt{R^2 + X^2}, \text{ or}$$
$$X = \sqrt{Z^2 - R^2}$$
$$= \sqrt{46^2 - 20^2}$$
$$= \sqrt{1716} = 41{\cdot}3 \text{ ohms.}$$

The power factor is $\cos\phi = \frac{R}{Z} = \frac{20}{46} = 0{\cdot}435$ lagging.

The power consumed is $P = VI \cos\phi = 230 \times 5 \times 0{\cdot}435 = 500$ W. All this goes into the lamps, as the reactor is assumed to have no resistance. As the lamps are non-inductive, $P = V_r I = 100 \times 5 = 500$ W, thus confirming that the power factor 0·435 is correct. (If a series resistor had been used instead of a reactor, the total power would have been $P = V \times I = 230 \times 5 = 1150$ W.)

The vector diagram is given in Fig. 23. It is worth noting that the volt drop across the reactor is $V_x = I \times X = 5 \times 41{\cdot}3 = 206{\cdot}5$ V, 90 deg. in advance of the current.

Condensers or capacitors are widely used in power circuits for improving the power factor of an inductive load, so reducing the current supplied through the mains. Let us find what capacitance put in parallel with the motor dealt with in the first example will raise the load power factor from 0·8 to 1. The frequency of supply is assumed to be 50~. The circuit arrangement is shown in Fig. 24.

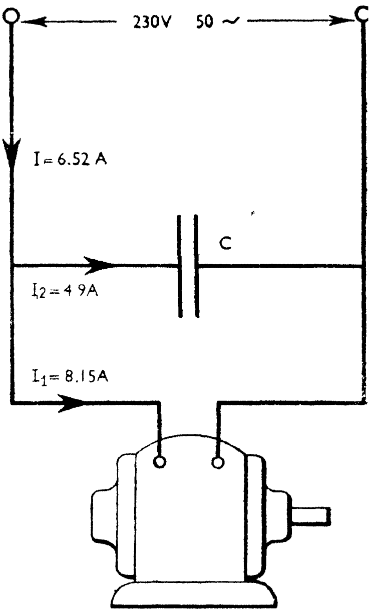


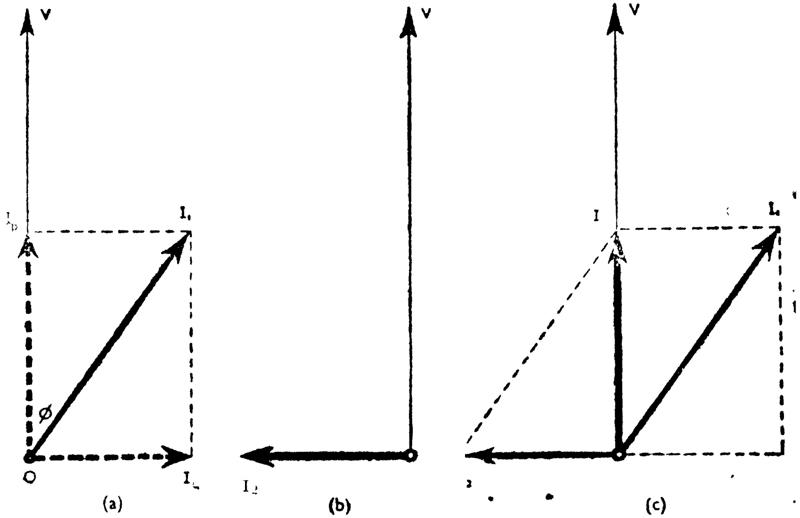
Fig. 24. Condenser *C*, across a motor taking a lagging current, advances the phase of the current taken from the supply. There is one value of capacitance which makes the overall power factor equal to unity. When the power factor is $\cos\phi$ the current is $\frac{\quad}{\text{volts} \times \cos\phi}$. This is least when $\cos\phi = 1$.

The motor alone takes a current of 8·15 A lagging behind the voltage by an angle ϕ, where $\cos\phi = 0{\cdot}8$. ($\phi = 36{\cdot}8$ deg. from tables.) Now this current, represented by OI_1 in Fig. 25a, can be imagined to be made up of two *components*, namely, I_p in phase with the voltage, and I_q lagging 90 deg. behind the voltage, as indicated in Fig. 25a.

The in-phase component I_p carries the total power of 1500 W, that is, $P = VI_p$, since there is no phase difference, and so $I_p = \frac{P}{V} = \frac{1500}{230} = 6{\cdot}52$ A (or, alternatively, $I_p = I_1 \cos\phi = 8{\cdot}15 \times 0{\cdot}8 = 6{\cdot}52$ A). This in-phase component I_p is called the *power component* of the current.

The component I_q lagging by

90 deg. represents zero average power, and is called the *wattless component*. To make the overall power factor of the circuit equal to 1 we must completely neutralize this lagging wattless current I_q by an equal *leading* wattless current, taken by the condenser. The vector diagram for the condenser alone is shown at (b) in Fig. 25.



VECTOR DIAGRAM SHOWING POWER FACTOR CORRECTION

Fig. 25. (a) The current I_1 is resolved into the power component I_p and the wattless component I_q. (b) Vector diagram of the condenser alone. (c) Combined vector diagram for the circuit of Fig. 24 for the condition of unity power factor. The leading current of the condenser completely neutralizes the lagging wattless current so that the line current is in phase with the voltage.

Referring again to (a), we have $I_1^2 = I_p^2 + I_q^2$, so that $I_q = \sqrt{I_1^2 - I_p^2} = \sqrt{8{\cdot}15^2 - 6{\cdot}52^2} = 4{\cdot}89$ A.

(Alternatively, $I_q = I_1 \sin\phi = I_1\sqrt{1 - \cos^2\phi} = 8{\cdot}15 \times \sqrt{1 - 0{\cdot}8^2} = 4{\cdot}89$ A; or, if the vector diagram is drawn to scale, the length of OI_q can be measured.)

To neutralize this the condenser must take a leading current of 4·89 A at 230 V 50~. Now, for the condenser, $I_2 = 2\pi fC \times V$, so that $C = \frac{I_2}{2\pi fV}$ farads, or,
$C = \frac{4{\cdot}89}{2\pi \times 50 \times 230} \times 10^6 = 67{\cdot}8\ \mu\text{F}$.

Complete Circuit Vector

With this value of capacitance in parallel with the motor, the two vector diagrams (a) and (b) of Fig. 25 become superimposed as you will notice at (c), giving the vector diagram for the complete circuit.

It should be noted that the line current I is now in phase with the voltage, indicating that the power factor of the circuit as a whole is equal to 1.

Also, it will be noted that the supply current is less than that taken by the motor, namely, 6·52 A, whereas the motor takes 8·15 A. Line losses are therefore reduced.

CHAPTER 8

ALTERNATORS AND SYNCHRONOUS MOTORS

BASIC PRINCIPLES. WAVE-FORM. FREQUENCY AND NUMBER OF POLES. INFLUENCE OF SPEED ON DESIGN. MECHANICAL CONSTRUCTION. SLOTS. ROTORS. TURBO-ALTERNATORS. GENERATED E.M.F. SINGLE-PHASE ALTERNATOR. BREADTH FACTOR. THREE-PHASE ALTERNATOR. PHASE SEQUENCE. THREE-PHASE CONNECTIONS. LINE AND PHASE VOLTAGES. MESH OR DELTA CONNECTION. POWER IN A THREE-PHASE SYSTEM. VOLTAGE CONTROL. MAGNETIZATION CURVE. ALTERNATOR ON LOAD. LOAD CHARACTERISTICS. OPERATION OF ALTERNATORS IN PARALLEL. SYNCHRONOUS MOTORS.

An alternator or A.C. generator is based on the same electromagnetic principles as the D.C. generator. Indeed, as already explained, the generated e.m.f.'s and currents in the armature conductors of a D.C. machine are actually alternating, but are given a single direction in the external circuit by the action of the commutator. No commutator is needed in an alternator, which is, therefore, comparatively simple and possesses several important advantages over the D.C. generator.

An alternator can be constructed either (*a*) with a rotating armature and stationary field magnet system, like a D.C. generator, but with slip-rings instead of a commutator, or (*b*) with a stationary armature and revolving field system. It is the absence of a commutator that makes the second arrangement possible and this is standard practice for all but the smallest machines.

In theory, it does not matter which of the two types is used, but, for practical reasons, medium and large machines are always constructed with the armature windings on the stationary part, called the *stator*.

The general form of slow- and medium-speed alternators is illustrated in Fig. 1. The armature core, on the inner surface of which are slots carrying the armature conductors, is supported in a cast-iron frame. The rotor is like a flywheel with the N and S poles fixed to the rim. Details of construction will be considered after discussing the basic principles.

Stationary Armature

The stationary armature arrangement has the advantages that:—

(*a*) the current can be led directly from the armature windings to the outgoing circuits without having to pass through brush contacts;

(*b*) the problem of insulating the armature windings is much simplified, as there are no centrifugal forces to cause mechanical strains, and

(*c*) the secure clamping of the end windings of large machines is rendered comparatively easy; such clamping is necessary to prevent bending in the event of short-circuit, when very large electromagnetic forces occur.

All these features make it possible to generate at high voltages.

In the stationary armature type, the field magnet windings are supplied, through two slip-rings, with *direct current* derived from a special *exciter* dynamo, usually built on the end of the alternator shaft. The exciting current is relatively small and the slip-rings and brushgear need be of only light construction.

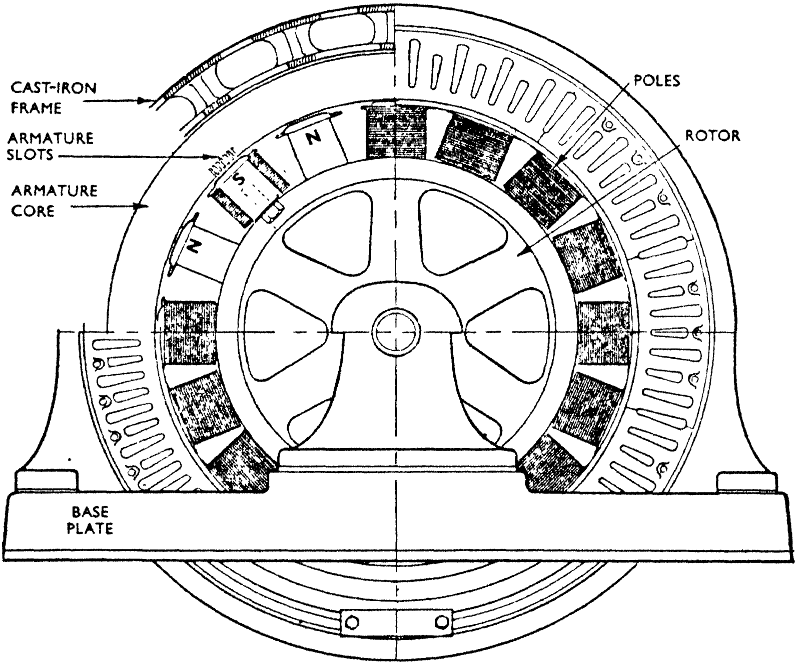
When a conductor is moved across a magnetic field so as to "cut" the lines of force, an e.m.f. is generated in it. The value of this e.m.f. is equal to,

Number of lines cut per second $\times 10^{-8}$ volts,

and its direction is given by Fleming's Right-hand Rule (*see* Chapter 3).

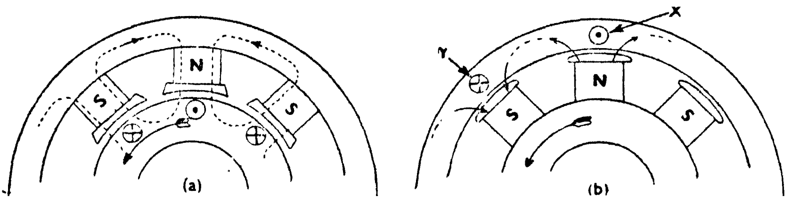
Applying this rule to Fig. 2a, which shows three armature conductors in a rotating armature machine, we find the e.m.f.'s directed as shown by the dot and the cross respectively. The dot represents the point of an approaching arrow, and the cross the end of a departing arrow.

When we come to consider the more usual arrangement shown at (b), with stationary armature and



MEDIUM-SPEED ALTERNATOR OF THE STATIONARY ARMATURE TYPE

Fig. 1. The armature core is supported by the cast-iron frame and is built of laminations of special magnetic iron alloy. The rotor is of the flywheel type, the poles being attached to the rim.



SIMPLIFIED DIAGRAM OF TWO FORMS OF ALTERNATOR

Fig. 2. Illustrating (a) rotating armature and (b) stationary armature types. The directions of e.m.f. are found by applying Fleming's Right-hand Rule. The dot at X represents the point of an approaching arrow, upwards through the paper, and cross at Y is feathered end of a departing arrow, downwards through the paper.

rotating field, we have to be careful how we apply the R.H. rule, for the thumb indicates the motion of the conductor *relative to the field.* To an observer stationed on one of the poles, the conductors would appear to be moving *clockwise.* So the thumb is pointed to the right. It is important to note that the e.m.f. in a conductor opposite a N pole is in the reverse direction to that in a conductor opposite a S pole.

The number of lines cut per second by a conductor is proportional to the strength of the field through which it is passing (as well as to its velocity of travel relative to the field). Thus, the generated e.m.f. is at all times proportional to the field strength where the conductor is. In other words, the e.m.f. is proportional to the air-gap field strength immediately opposite the conductor.

If we plot a curve representing the field strength along the armature surface, in the manner shown by Fig. 3, where flux entering the armature (opposite N pole) is positive and that leaving is negative, we get a wave as illustrated. If the air-gap length between pole face and armature surface is uniform, the flux wave will be flat-topped. The alternating e.m.f. generated in each conductor has exactly the same shape as the wave of flux distribution.

Now, the ideal wave is sine-shaped and to approach this ideal some means must be adopted to distribute the flux along the armature surface accordingly. In alternators with definite or *salient* poles, this can be done by judicious shaping of the pole shoes. The field strength is almost inversely proportional

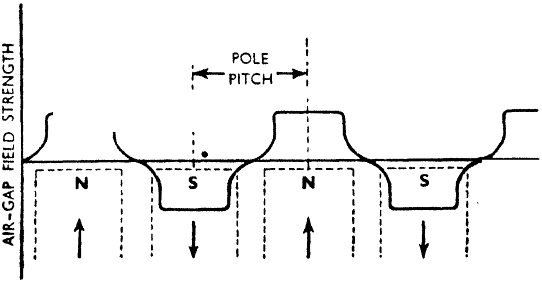


Fig. 3. Graph showing field strength along armature surface. Vertical distances above base line represent flux entering armature and vice versa. With constant air-gap length the wave is flat-topped.

to the air-gap length at any point, so it is theoretically possible to shape the pole faces to give true sine distribution.

This is clearly to be seen by examining Fig. 4, where the air-gap widens from centre to pole tip.

In many turbo-alternators there are no definite poles, as explained further on, and satisfactory flux distribution is achieved by suitable arrangement of the conductors carrying the exciting current.

Speed and Frequency

Let us now consider the e.m.f. generated in conductor *X* of Fig. 2b as the N and S poles pass it. One positive half-cycle will be generated (towards us) as a N pole passes and one negative half-cycle as the succeeding S pole passes.

It will be found, therefore, that one complete cycle of e.m.f. is generated during the passage of one *pair* of poles, that is, one N pole and the adjacent following S pole.

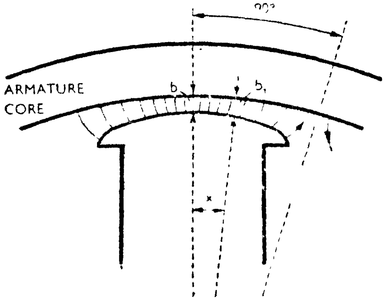


Fig. 4. Pole face shaped so that the air-gap length increases from the pole centre towards the pole tips. This is done to distribute the flux over the armature surface to give approximately a sine wave. Theoretically, a pure sine wave is obtained if $b_1 = \frac{b}{\cos x}$. The angle marked 90 deg. (electrical) is the angle of rotation for a quarter cycle of e.m.f. or 90 deg. of vector rotation. The angle of rotation giving one complete cycle is 360 electrical deg. and is the angle between two N poles with one S pole in between.

If, then, the machine has p pairs of poles (p north poles and p south poles) on the rotor, p cycles of e.m.f. will be generated during every revolution. So if the speed of the rotor is n revolutions per second, there will be $p \times n$ cycles generated every second. In other words, the frequency will be,

$$f = p.n \text{ cycles per second.}$$

If N is the speed in revolutions per *minute*, the frequency is

$$f = \frac{p.N}{60} \text{ c.p.s.}$$

The speed for which an alternator is designed depends on the nature of the "prime mover," that is, on the turbine, engine or waterwheel to which it is coupled.

Steam turbines operate at very high speeds, driving alternators up to 3600 r.p.m., whereas large water turbines run at low speeds.

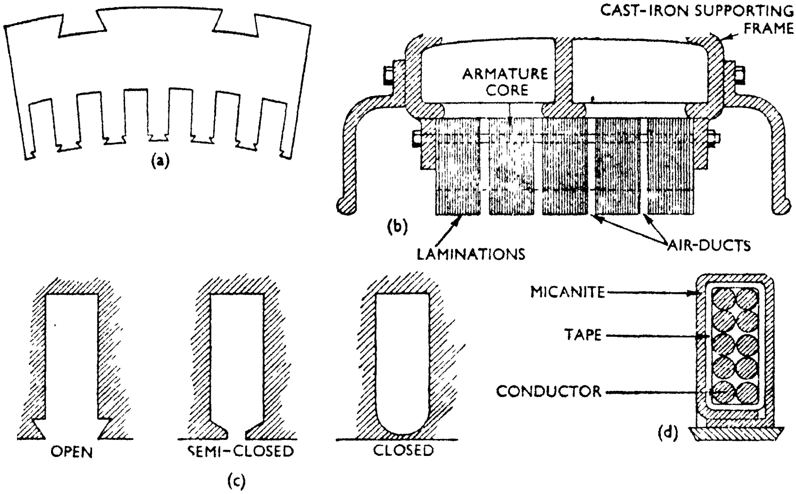
To give some specified frequency, such as 50 cycles per second, the number of pole pairs must be suitably related to the running speed. At a speed of N r.p.m. the number of pole pairs required is,

$$p = \frac{60\,f}{N}.$$

An alternator to give 50 cycles at 150 r.p.m. must have $p = \frac{\times 50}{150}$ = 20 pole pairs or 40 poles. To give 50 cycles at 1500 r.p.m. the number of pole pairs would be $p = \frac{60 \times 50}{1500} = 2$, or 4 poles.

We see that slow-speed alternators have large-diameter rotors with many poles, and high-speed machines have relatively small diameters with few poles. So the size and general design of a machine depend primarily on (*a*) output and (*b*) speed.

Slow- and medium-speed alternators are invariably of the flywheel



DETAILS OF STATIONARY ARMATURE ALTERNATORS

Fig. 5. (a) Armature stampings pressed out of sheets of special magnetic iron or steel alloy. In the smaller sizes the stampings are pressed out in complete rings. (b) Section through top of stator of Fig. 1. The armature core is built up of laminations which are held tightly together by end clamping rings. Spacing strips inserted at intervals leave ducts for cooling air to pass through. The air is driven through by the fan action of the rotor and escapes via the apertures in the cast-iron supporting frame. (c) Types of armature slots. The filled slot (d) has round wires, but it is common to have rectangular conductors to economize slot space.

type illustrated in Fig. 1, although some hydro-electric generators (those driven by water turbines) have their shafts in the vertical position to suit the requirements of the turbines.

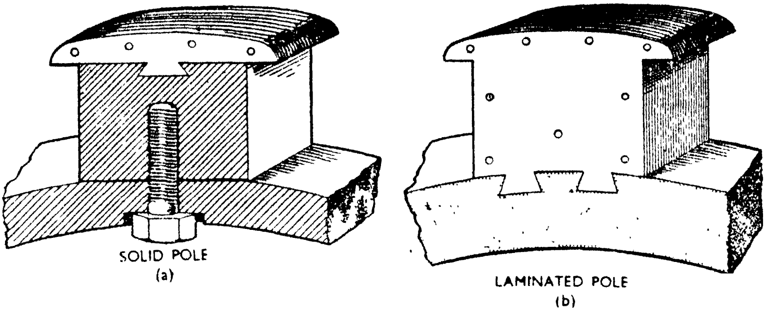
High-speed turbo-alternators always have either four or two poles and the rotors must necessarily be of relatively small diameter to limit centrifugal forces at these high speeds; the diameter being between one-third and half the axial length.

The general form of slow- and medium-speed alternators is illustrated in Fig. 1. The armature core is built up of laminations or sheets of special magnetic iron or steel alloy and is supported by the hollow cast-iron frame. The core has to be laminated to prevent the flow of heavy "eddy currents" which would otherwise be generated in the iron by the moving magnetic flux.

The laminations are stamped out in complete rings, or in segments according to the armature diameter. The construction is shown in Fig. 5a and b. Spaces are provided at intervals between the laminations to allow cooling air to pass through. The laminations themselves are insulated from each other by varnish or paper coating.

Types of Slot

The slots for carrying the armature winding are stamped out in one operation when the laminations are formed. There are three types, as illustrated at (c) in Fig. 5. The open type has the advantage of allowing former-wound coils to



POLE CONSTRUCTION FOR FLYWHEEL-TYPE ALTERNATORS

Fig. 6. It has been found that the pole caps or shoes must be laminated to reduce eddy current losses and heating caused by concentrations of flux opposite the armature teeth and subsequent reduction opposite slots.

be used and laid in whole. The main disadvantage is that the flux in the air-gap is gathered into bunches which generate ripples in the e.m.f. wave.

The semi-closed slot is better in this respect but does not permit the use of former-wound coils. The closed slot is the best from the point of view of air-gap flux disturbance, but the conductors have to be threaded through and the problem of end connections is much complicated.

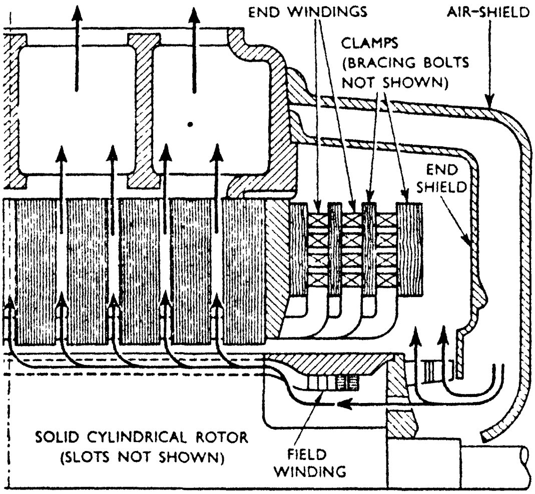


Fig. 7. Simplified sectional drawing showing features of a turbo-alternator. The rotor is turned from a steel forging and slotted to carry the exciting windings, the slots being arranged as in Fig. 8b. Because of the high running speed, alternators for large outputs have considerable axial length compared with rotor diameter.

The flywheel type of rotor is constructed to give adequate mechanical strength to withstand centrifugal and driving forces and at the same time to provide the necessary paths for the magnetic fluxes. The poles may be either solid or laminated, and examples of construction are illustrated in Fig. 6.

In any case, the *pole shoes* or pole caps are laminated because the armature teeth between the slots cause concentrations of flux which generate e.m.f.'s in the pole shoes. If they were not laminated the resulting eddy currents would cause excessive loss and heating.

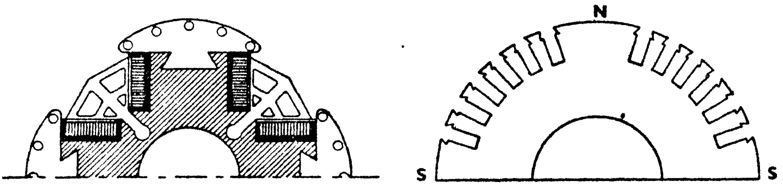
The poles are wound with ordinary wire coils for the smaller sizes, but in larger machines the field windings are made of rectangular copper strip wound on edge. The latter arrangement gives good mechanical strength and wastes less space. Copper bars are usually embedded in the pole shoes and riveted to heavy end-plates partly to counteract the effects of tooth ripple and partly to enable alternators to run satisfactorily in parallel, as explained later.

The stator construction for turbo-alternators is on the same lines as for slow-speed machines, but the ratio of diameter to axial length is very much less. The general form of a turbo-alternator is shown in Fig. 7.

Rotor Design

The rotor is designed to withstand the high speed of operation and never has more than four poles. Two forms are illustrated in Fig. 8. The one shown at (a) has definite or salient poles and is to be found in many machines in operation. But, in general, all large modern alternators have solid steel cylindrical rotors as shown at (b) with the magnetizing winding carried in groups of slots and fed through a pair of slip-rings on the shaft. By suitable spreading of the windings the flux is distributed over the surface approximately according to a sine law.

The solid rotor makes the use of semi-closed or closed armature slots essential and damping bars are unnecessary. The solid cylindrical rotor has considerable advantages both in strength and noiseless operation.



(a) (b)

CONSTRUCTION OF ROTORS FOR TURBO-ALTERNATORS

Fig. 8. (a) Definite pole or salient pole type. This form is found in many machines in operation but has given place in modern machines to (b), the solid steel cylindrical rotor. This has the advantages of great strength and stiffness. The axial length is usually considerably greater than the diameter. The exciting current is carried by bar-type conductors in the groups of slots shown. All currents in one group are in the same direction, those in the next group in the opposite direction. Flux produced is distributed over surface approximately according to sine law.

Referring back to Fig. 2b, and assuming sine wave distribution of flux in the air-gap between each pole face and the stator core, the generated e.m.f. wave will be sine-shaped as in Fig. 9a.

Let the flux crossing the air-gap to or from each pole be Φ lines (maxwells). Then, if there are p pole pairs or $2p$ poles, the total flux crossing the air-gap in both directions is $2p\Phi$ lines, and the whole of this flux is cut by each conductor during one revolution. If the speed is *n* revolutions per second, the *total* flux cut per second by a conductor is $2p\Phi n$ lines.

But, as we saw earlier, the frequency is $f = p.n$, so that the conductor cuts $2f\Phi$ lines per second and the average generated e.m.f. is, therefore, $2f\Phi \times 10^{-8}$ volts per conductor.

Form Factor

In getting this result we have argued as though all the flux crosses the air-gap in one direction, ignoring the fact that half of it crosses in each direction. The average e.m.f. is the average value of the "rectified" sine wave of Fig. 9b—the average value of curve (a) would be zero.

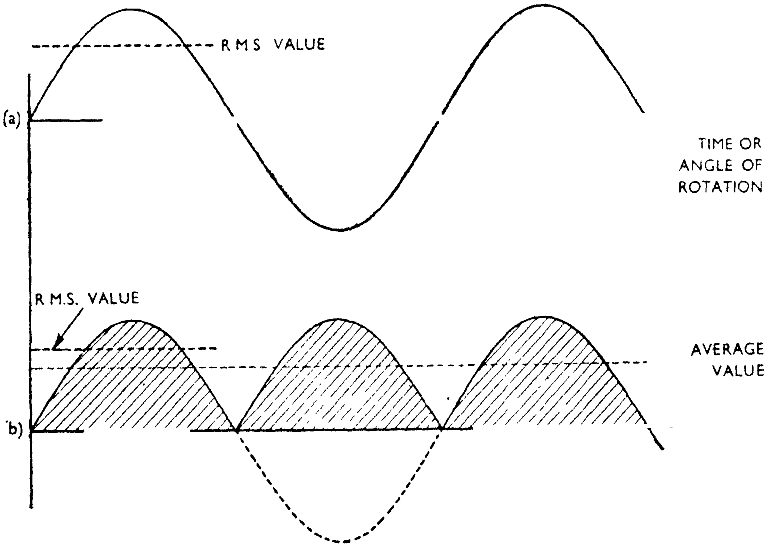
For a sine wave, it can be shown that the R.M.S. or effective value is 1·11 times the "average" value. This number is the *form factor* of the sine wave. So the R.M.S. value of the e.m.f. generated in one conductor is,

$$V = 1{\cdot}11 \times 2f\Phi \times 10^{-8} = 2{\cdot}22\ \Phi f \times 10^{-8} \text{ volts},$$

where Φ is the useful flux per pole, that is, the flux actually passing from the pole to the armature core, as distinct from *leakage flux* which jumps across from pole to pole without entering the stator.

For other than sine waves, the form factor would be different from 1·11.

The e.m.f. in one conductor is not very great and, to get a high voltage from the machine, a number of conductors have to be connected in series in such a way that their e.m.f.'s add together. There are



R.M.S. VALUE AND FORM FACTOR

Fig. 9. (a) Sine wave of e.m.f. in one conductor when the air-gap flux is distributed according to a sine wave. (b) Rectified sine wave used in calculating the R.M.S. value of the e.m.f. The ratio, $\frac{\text{R.M.S. value}}{\text{Average value of a half wave}}$, is the form factor of the wave, being 1·11 for a sine wave.

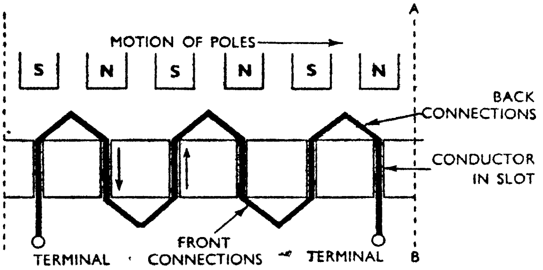


Fig. 11. Developed diagram of Fig. 10. The stator core is imagined to be cut at *AB* and opened out into a flat surface with the slots uppermost, and then viewed from the top. The slots and conductors are spaced exactly one pole pitch apart, the pole pitch being the distance between the centres of two adjacent poles, measured along the armature surface. The winding is called a bar winding, or wave winding, from its appearance.

several ways of doing this, leading to different types of armature windings.

In a single-phase machine, all the conductors are connected in series in a single circuit.

Let us take the simplest possible arrangement first, an alternator with the same number of slots in the armature core as there are poles, as illustrated in Fig. 10. Here there are six poles and six slots and it will be assumed that there is one conductor in each slot for simplicity. The conductors are spaced one *pole pitch* apart, a pole pitch being the distance between two pole centres measured along the curved surface of the armature.

The arrow shows the direction of rotation and the dots and crosses indicate the direction of current flow in the armature conductors.

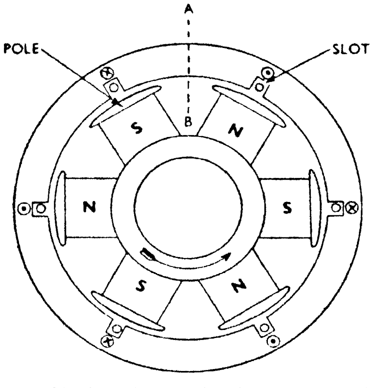


Fig. 10. Simple 6-pole alternator with as many slots as poles—one slot per pole. Each slot carries one conductor and these are all connected in series to form the simple wave winding of Fig. 11.

It is not easy to show clearly the connections between the conductors at both ends of the machine in such a diagram as Fig. 10. The best thing is to "develop" a diagram as in Fig. 11, where the armature core is imagined to be opened out into a flat surface with slots uppermost and viewed from the top. The positions of the poles corresponding to Fig. 10 are shown in the upper part, the dot line *AB* showing the start and end.

Total e.m.f.

The conductors are represented by the heavy lines and are all connected in series by back and front connections, giving a simple wave or bar winding. The total voltage is equal to the e.m.f. per conductor multiplied by the number of conductors, since all the e.m.f.'s are in phase and in series.

It is seldom that one conductor per pole will give anything like the required voltage. So let us go a stage further and suppose that there are three conductors per pole, each in its own slot, the slots being grouped as in Fig. 12a.

We can connect the three corresponding groups of conductors as before, and all three can be connected in series, giving the *distributed wave winding* shown in Fig. 13a.

Now, in such a distributed winding, the e.m.f.'s of the (three) groups are slightly out of phase, as shown by the e.m.f. waves of Fig. 12b, so the total R.M.S. voltage will be equal to their *vector sum*, represented by *OA* in Fig. 12c. This is slightly less than their arithmetical sum.

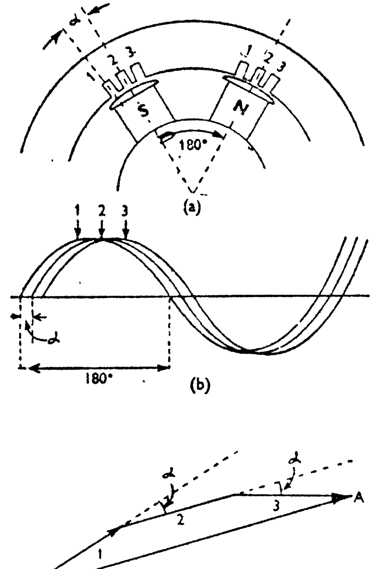


Fig. 12. (a) Single-phase alternator with three slots per pole. The angle between the axes of two adjacent poles corresponds to a half-cycle of e.m.f. and is denoted by 180 electrical deg. (b) The sine waves show the phase difference between e.m.f.'s in conductors in adjacent slots. (c) Vectors representing the e.m.f.'s in the three conductors in a group of slots. When the conductors are in series their total e.m.f. is given by the vector sum of the individual e.m.f.'s. The vector sum *OA* is less than arithmetical sum of the three e.m.f.'s.

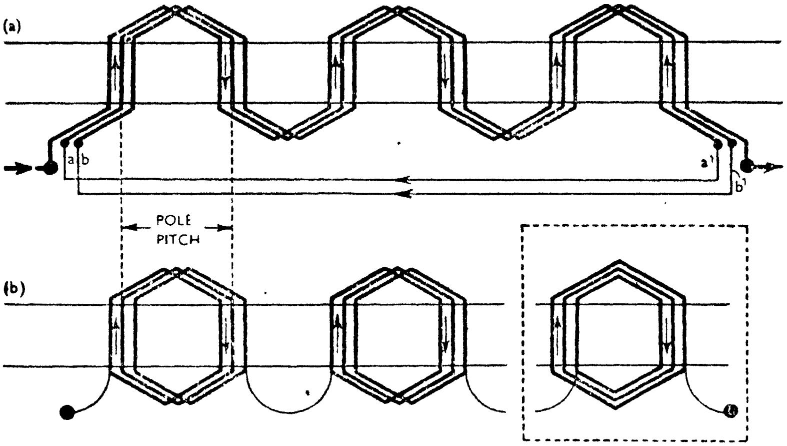
If all the conductors had been concentrated in a single slot per pole, the total voltage would have been $V = 2{\cdot}22 f \Phi \times 10^{-8} \times$ (total number of conductors). But when the conductors are spaced apart into adjacent slots, as they must be, we have to multiply by what is known as the *distribution factor* (*k*), which is less than 1 and depends on the angular spacing *a* of the slots in any group and the number of slots per pole.

The voltage equation becomes, $V = k \times 2{\cdot}22\, f\Phi \times 10^{-8} \times$ (total number of conductors), with sine wave flux distribution.

Usually there are too many conductors to allow only one per slot, so that coils are made up, each containing a number of turns, each turn comprising *two* effective conductors. The two sides of a coil are equal to or nearly equal to one pole pitch apart. In the simplest arrangement there is one coil-side per slot, giving a single-layer distributed lap winding as in Fig. 13b.

There are several other possible arrangements with both single- and double-layer windings. In the latter type, the side of one coil is at the bottom and the side of another coil at the top of each slot —exactly as in a D.C. armature winding.

Nearly all alternators are designed for three-phase working because, compared with single phase: (*a*) a much greater output can be obtained from a machine of the same size; (*b*) the performance is superior; the driving torque or



SINGLE-PHASE ARMATURE WINDINGS

Fig. 13. (a) Distributed wave or bar winding with three conductors per pole. a—a^1 are joined and b—b^1 are joined, giving a complete single series circuit. (b) Distributed coil winding. On left, all coils are same shape and span of each coil is equal to pole pitch. On the right (inset) three coils of a group are of different pitches or spans. All coils are in series—not shown in diagram.

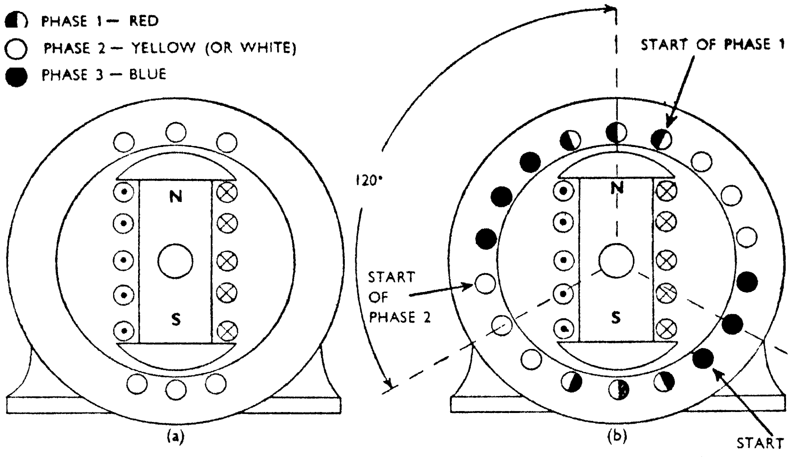
force required is constant, since the sum of the instantaneous powers from the three phases is the same at all times, resulting in absence of vibration and noise; (*c*) three-phase transmission of power is superior and more economical; (*d*) three-phase motors are superior to and less costly than single-phase.

To illustrate the principle, let us consider a simple 2-pole alternator as represented in Fig. 14. At (a) we have an elementary single-phase machine, showing considerable wasted space where there are no windings. In an actual machine some of this space would be used for additional windings, but only about two-thirds of the whole space can be usefully employed owing to the effects of the distribution factor. In (b) there are two additional armature windings, the slots being evenly spaced over the whole surface. Each of the three windings is essentially a single-phase winding and all three are exactly alike.

If so desired, each phase winding can be connected independently to a separate load, but this is not usual as there are better arrangements, to be explained presently. It is normal practice to distinguish the phases by colour markings at the terminals, usually red, yellow (or white) and blue, and these are suitably indicated in Fig. 14b.

Phase Differences

For the position of the rotor shown, phase 1 has its maximum e.m.f. Phase 2 *begins* 120 deg. further round the stator, so that its maximum e.m.f. will occur when the field magnet has revolved a further 120 deg. Since one cycle is generated in each phase during one revolution (for the 2-pole machine), it follows that the e.m.f. in phase 2 will lag 120 deg. behind the e.m.f. in phase 1. Similarly, the e.m.f. of



THREE-PHASE TWO-POLE ALTERNATOR

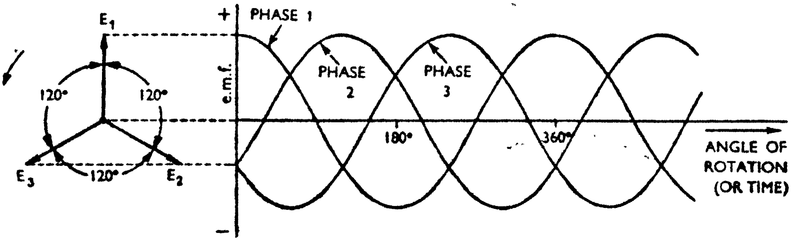
Fig. 14. Alternator diagrams simplified to illustrate the essential difference between single-phase and three-phase machines. (a) Single-phase machine in which the winding is concentrated into somewhat narrow bands on the armature surface, a considerable part of which carries no conductors. (b) Three-phase arrangement, in which the whole of the armature core is utilized. There are three independent windings, each similar to the single-phase winding of (a). The angular spacing of the three windings is 120 deg., so that their e.m.f.'s are out of phase successively by 120 deg. If desired, each phase winding can be connected independently to a separate load.

phase 3 lags 120 deg. behind that of phase 2.

Therefore, the three e.m.f.'s are successively 120 deg. out of phase and are represented by the vectors E_1, E_2 and E_3 and by the sine waves of Fig. 15.

The important things to notice are that the voltage vectors are 120 deg. apart and that, from the sine waves, *the sum of the three e.m.f.'s is zero at every instant.* This is of importance when we come to consider methods of connection.

The order in which the three voltages in the phases reach their maximum positive values is called



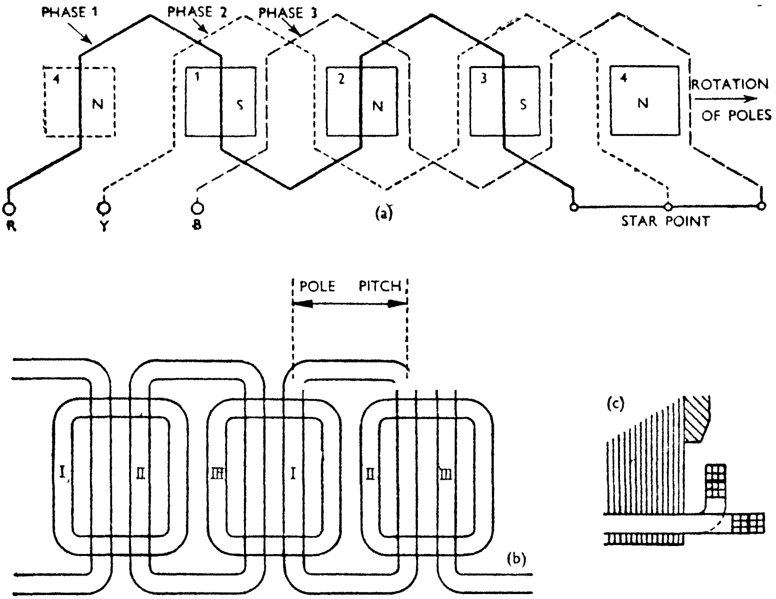
THREE-PHASE VECTORS AND SINE WAVES

Fig. 15. Phase sequence is the order in which the three e.m.f.'s pass through their maximum positive values, or the order in which the rotating vectors pass a given point. An important feature is that the three e.m.f.'s add up to zero at all times.

the *phase sequence* and is given by the order in which the rotating vectors of Fig. 15 pass a given point. In this case, the sequence is E_1, E_2, E_3.

Cable ends and three-phase transformer terminals are usually coloured, lettered or numbered, so that the correct sequence is maintained when connecting up.

A three-phase armature winding is, as a whole, more complicated than the winding of a single-phase machine, because of the comparatively large number of end windings or end connections that have to cross over each other. The armature coils are sometimes built up in formers and they are then inserted in the armature slots.



BAR AND COIL THREE-PHASE WINDINGS

Fig. 16. (a) Simple bar type or wave winding. The three phases are shown star connected as in Fig. 17c. (b) Coil winding with two coil shapes, whilst (c) shows how the end windings are arranged to cross over each other.

Here, again, there are several possible arrangements. For instance, there can be three simple wave windings, as in Fig. 16a, evenly spaced, or three distributed wave windings each like that of Fig. 13a.

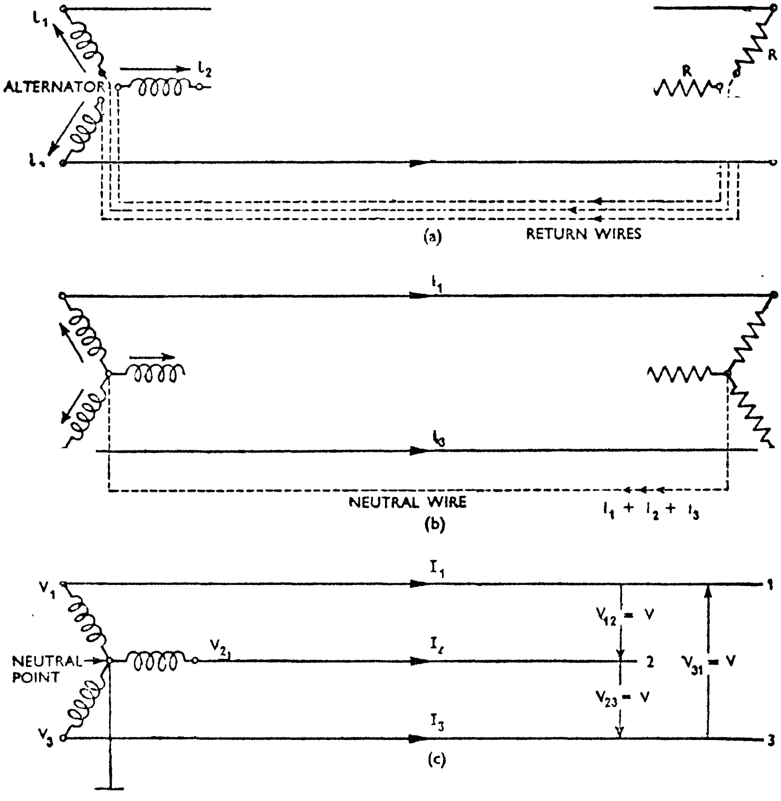
As a rule, the number of conductors required is large enough to make windings with coils necessary. An example is illustrated in Fig. 16b.

As the coil ends have to cross over each other, some of them are bent outwards from the centre of the machine into different planes as indicated in Fig. 16c.

In a theoretical diagram, it is convenient to represent the three individual phase windings of the alternator by three coils with their axes displaced 120 deg. as in Fig. 17a. The angles between the axes then represent the phase differences between the corresponding voltages.

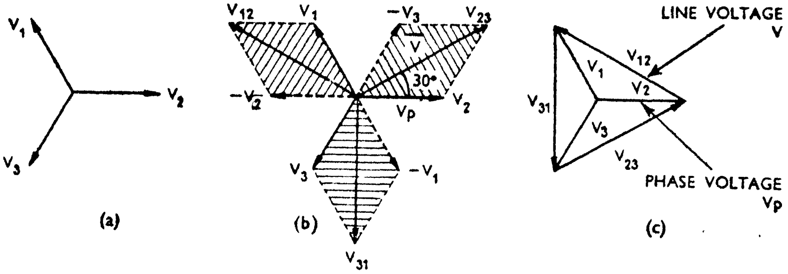
Now, suppose that a resistance R is connected across the terminals of each phase winding, all three resistances being equal. Each phase then supplies an independent single-phase "load" through its own pair of leads, all three groups being entirely insulated from each other. The circuits are shown in Fig. 17a, the rather strange arrangement being for reasons that will soon become apparent.

In three-phase work, one has to be very careful and systematic in



STAR OR Y CONNECTION OF THREE-PHASE ALTERNATOR

Fig. 17. At (a) each phase winding supplies an independent load through a pair of leads. This requires six wires. At (b) a four-wire system is obtained by connecting the three "return" wires of (a) in parallel and then replacing them by a single wire, called the *neutral wire*. When the load is balanced the sum of the three currents "returning" through the neutral wire is zero. So for a balanced load the neutral wire is unnecessary and the three-wire system shown at (c) may be used. The neutral point of the alternator is usually earthed directly or through a reactor.



SHOWING RELATIONSHIP BETWEEN LINE AND PHASE VOLTAGES

Fig. 18. V_1, V_2 and V_3 are the phase voltages, being the voltages between the corresponding line conductors and the neutral point. V_{12} is the voltage reckoned from line 1 to line 2, and so on. So V_{12} is the vector difference $V_1 - V_2$, found by reversing the V_2 vector and adding it vectorially to V_1. The three line voltages are given by the diagonals of the shaded parallelograms. Each line voltage V is equal to $\sqrt{3}$ times the phase voltage V_p. (c) is a simplified diagram giving the same results.

the use of arrows and signs giving directions. The first important thing to keep in mind is that arrows indicate *positive* directions (not the actual directions at any instant), and that the e.m.f.'s and currents are never all positive at the same time.

In Fig. 17a the e.m.f.'s of the phase windings are shown directed outwards from the centre *when positive.*

Now, the corresponding *positive* directions of the currents in the leads are also shown but, in actual fact, the three currents in the "outgoing" leads are not all positive at the same time.

The currents "return" *via* the broken-line conductors shown grouped together. Now, there is nothing to prevent us from joining all these three return wires in parallel, or from replacing them by a single wire of sufficient section to carry the total return current $i_1 + i_2 + i_3$, as in Fig. 17b. This arrangement is called the *star* or Y connection, with "neutral" wire. It gives us the familiar four-wire three-phase system.

The total load is said to be *balanced* when all three of its phases are identical, as in this case. So the three currents i_1, i_2 and i_3 will be represented by three sine waves of equal maximum value and displaced by 120 deg., as in the case of the e.m.f. waves shown in Fig. 15.

Neutral Wire Unnecessary

As pointed out previously, their sum is zero at every instant, and so *with a balanced load the neutral wire carries no current.* It can be dispensed with altogether, leaving the star-connected arrangement of Fig. 17c. This gives a three-wire three-phase system.

The *neutral point* or star point at the junction of the phases is usually connected to earth so that each line conductor or alternator terminal has the same R.M.S. voltage to earth or to the frame of the machine. Another advantage is that no point in the system can have a higher voltage to earth than the phase voltage when an accidental earth occurs.

If V_1 and V_2 are the potentials (that is, the voltages with respect to earth) of two points, the potential difference between the points is $V_1 - V_2$. Therefore, if V_1, V_2 and V_3 are the R.M.S. voltages of the star-connected alternator terminals with respect to neutral (or earth), the R.M.S. voltage from line 1 to line 2 in Fig. 17c is $V_{12} = V_1 - V_2$. But this is not the simple arithmetical difference, because we are dealing with alternating voltages out of phase. It is the *vector difference*.

It can be shown that the voltage between any two conductors is $\sqrt{3}$, or 1·73 times the voltage between one line and neutral. To take an easy example, if the voltage between one line and neutral in a three-phase system is 100, then the voltage between any two lines is 100 × $\sqrt{3}$, or 173 V.

Voltage to Neutral

Similarly, if the voltage between lines is known, the voltage to neutral is obtained by dividing by $\sqrt{3}$.

For those interested, the vector diagram by which these voltage relationships are calculated is given in Fig. 18. From the trigonometry of any one of the shaded parallelograms,

$$\begin{aligned} V &= 2Vp \cos 30 \text{ deg.} \\ &= 2Vp \times \frac{\sqrt{3}}{2} \\ &= \sqrt{3}Vp. \end{aligned}$$

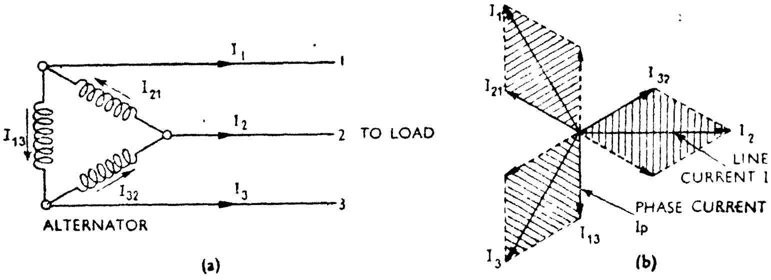
Assuming balanced load, which is usual, the R.M.S. current I in each line conductor is equal to the R.M.S. current I_p in each phase winding, as each conductor is in series with one of the phase windings, so that

$$I = Ip.$$

Mesh or Delta Connection

We have seen that the e.m.f.'s in the three-phase windings add up to zero at every instant. For this reason, all three windings can be connected to form a closed loop or mesh as in Fig. 19a, provided the *positive* directions of e.m.f.'s are all directed the same way round the loop. No circulating current will be produced in the loop, as the resultant of all three e.m.f.'s is at all times zero.

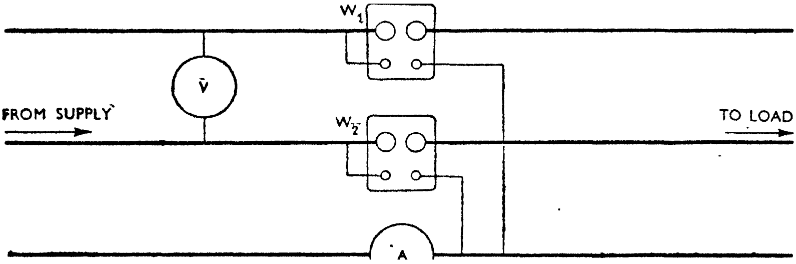
As any one pair of line conductors is connected directly across one phase winding, each line voltage is equal to each phase



(a) (b)

MESH OR DELTA CONNECTION

Fig. 19. This connection is permissible because the vector sum of the e.m.f.'s in the three-phase windings is zero. Here the line voltage is equal to the voltage of each phase winding, but the current in each line conductor is equal to $\sqrt{3}$ times the current in each phase winding. This is shown by the vector diagram at (b), as explained in the text. There is no neutral point with this connection.



MEASURING THE POWER IN A THREE-PHASE LOAD

Fig. 20. Connections of two wattmeters, an ammeter and a voltmeter for measuring the power and power factor of a balanced three-phase load.

voltage, namely, $V = Vp$. There is no neutral point.

On the other hand, the current in any one conductor is divided between the *two* phases connected to that conductor. Now, according to Kirchhoff's Law, the sum of the currents leaving a junction is equal to the sum of the currents approaching it, and with A.C. this applies to the *vector sum* in each case.

The complete vector diagram for line and phase currents is shown at (b) in Fig. 19 for balanced load conditions. The diagram is similar to Fig. 18b for star voltages, and each of the line currents is seen to be equal to $\sqrt{3}$ times the phase current. So for mesh connection,

$$I = \sqrt{3}I_p.$$

It is permissible to argue that, as each line conductor is supplied by two phases, the line current is greater than the phase current.

Three-phase Power

Let us suppose that we have a three-phase load made up of three identical impedances connected either in star or in delta (mesh) or consisting of a motor with its windings either star- or mesh-connected.

It is impossible to deal fully with the theory of A.C. machines and circuits without introducing some trigonometry, although if the reader is unable to understand such calculations as the following, a great deal of useful knowledge can be acquired by memorizing the principles with which they are associated.

Now, if V_p is the voltage across each phase, I_p the current in each phase, and ϕ the phase angle between V_p and I_p, then the power in one phase is $V_pI_p \cos\phi$ watts, where $\cos\phi$ is the power factor.

For all three phases the total power is, $P = 3V_pI_p \cos\phi$ watts.

If the load is star-connected, $V_p = \frac{V}{\sqrt{3}}$ and $I_p = I$, where V is the line voltage and I is the line current. On the other hand, if the load is mesh-connected, $V_p = V$ and $I_p = \frac{I}{\sqrt{3}}$. So, for *either method of connection*, $V_pI_p = \frac{VI}{\sqrt{3}}$, and the total power is,

$$P = 3\frac{VI}{\sqrt{3}}\cos\phi, \text{ or}$$

$$P = \sqrt{3}VI\cos\phi.$$

This gives the total power in a balanced three-phase load in terms of line voltage and current. It has to be remembered that $\cos\phi$ is the power factor of each individual phase, ϕ being the phase angle between the voltage and current of any one phase (not between line voltage and current).

The power in a three-phase load on a three-wire system is usually measured by two wattmeters, W_1 and W_2, connected as shown in Fig. 20. Whether the load is Y or Δ connected, or whether part of it is Y and part Δ connected, does not matter. It can be shown that in all circumstances the total power is equal to the sum of the wattmeter readings, $P = W_1 + W_2$.

If the load is balanced, so that all three line currents are equal, the total *volt-amperes* is $\sqrt{3}VI$, where V is the line voltage and I is the current per line conductor. The power factor of the load is then,

$$\text{P.F.} = \cos\phi = \frac{P}{\sqrt{3}VI}.$$

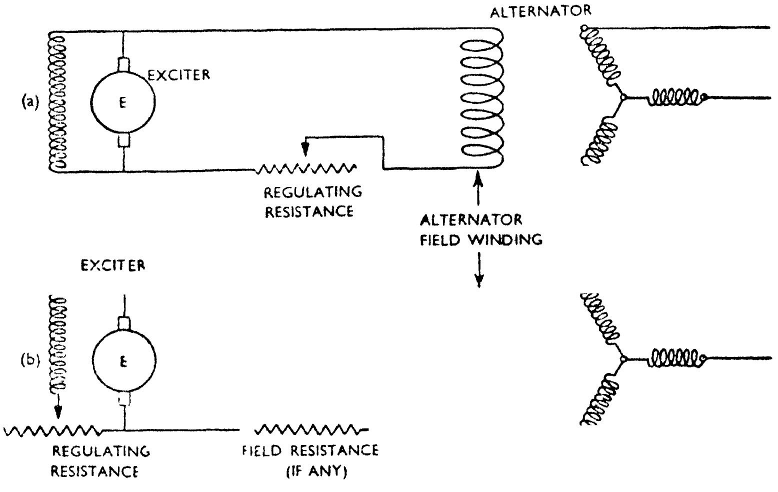
High-voltage alternators are always star-connected, because this enables each winding to be designed for only $\frac{1}{\sqrt{3}}$, or 0·577 of the terminal voltage. In addition, a neutral point is available for earthing.

We have seen that the generated e.m.f. is proportional to the useful flux per pole and to the speed or frequency. The useful flux is that actually passing into the armature core. As an alternator is run at fixed speed to give a constant frequency, the generated e.m.f. can be altered only by varying the flux per pole, that is, by variation of the field strength.

Excitation

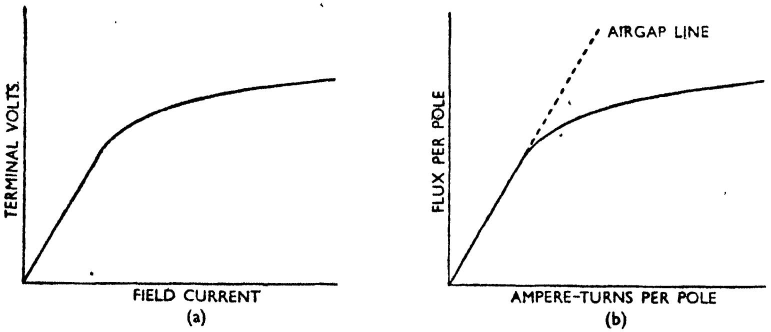
Since the field strength depends on the D.C. exciting current in the field magnet coils, we regulate the exciting or field current accordingly to adjust the output voltage.

For small alternators, this is done by means of an adjustable resistance in the alternator field circuit, but with large machines the field current might be as high as 400 A, and easier control is got by connecting the regulating



VOLTAGE CONTROL OF AN ALTERNATOR

Fig. 21. (a) Variable resistance in alternator field circuit. (b) Variable resistance in shunt field circuit of the exciter. The latter is used in the case of larger machines.



MAGNETIZATION CURVES

Fig. 22. (a) Open-circuit or no-load characteristic of an alternator showing how the terminal voltage varies with exciting current. It is frequently called the magnetization curve, but this applies more strictly to the curve shown at (b), where flux per pole is plotted against exciting current. The open-circuit terminal voltage is proportional to the useful flux per pole.

resistance in the field circuit of the *exciter*, where comparatively low current has to be handled. The two systems are shown at (a) and (b) in Fig. 21.

We shall see presently that the terminal voltage of the alternator depends not only on the exciting current but also on the load current and the power factor of the load. But, for the present, we shall consider the no-load conditions, when the voltage at the terminals of each phase winding is equal to the e.m.f. generated in it. If the alternator is star-connected, the terminal voltage at no load is equal to $\sqrt{3}$ times the e.m.f. in each phase winding.

If we measure the no-load terminal voltage for various values of exciting current, with the machine running at normal speed, and plot one against the other as a graph, we get the *magnetization curve* or *open-circuit characteristic*. This has the form shown in Fig. 22a.

As the voltage is exactly proportional to the flux per pole, a curve of flux per pole plotted against ampere-turns per pole has the same shape, and the term "magnetization curve" applies more strictly to the latter case, which is represented in Fig. 22b.

The magnetization curve is determined by the properties of the magnetic circuit. The flux of each pole divides into two equal parts in the armature core and the total flux is divided up into as many loops as there are poles. We need consider only one of these loops, as we find that they are all alike.

Effect of Air-gaps

Each line of force lies within an iron path over most of its length, but crosses two air-gaps. At low flux densities, when the magnetizing current is low, the permeability of the iron is very high, so that, compared with the air-gaps, the iron offers very little *reluctance*, or magnetic opposition, to the flux. For air, the permeability is 1 at all flux densities and, therefore, at the lower end the magnetization rises uniformly with magnetizing current. As the current is increased and the flux density in the iron rises, the permeability begins to fall and to check the rise of flux. This causes the falling away of the curve from the "air-gap line" in Fig. 22b.

Beyond the bend of the curve, the magnetic circuit is said to be *saturated*, and the magnetization curve is sometimes called the *saturation curve.*

Alternator on Load

If we adjust the excitation of an alternator to give normal voltage at no load, and then apply a load, we find that the terminal voltage changes, even though the speed is kept constant. The voltage usually falls, but in certain circumstances it may actually rise.

There are three reasons for these changes, namely (*a*) the resistance of each phase winding; (*b*) the reactance of each phase winding, and (*c*) *armature reaction*, which is the name for the disturbing effects on the main field caused by magnetic fluxes produced by the armature currents.

Let us consider these effects separately. (*a*) If R is the resistance of each phase winding and I is the current, a voltage IR, in phase with the current, is absorbed in overcoming the resistance. (*b*) Each phase of the winding has reactance X ohms, represented by fluxes set up around the winding but not passing into the main field magnets. This results in a volt-drop IX leading a quarter-cycle on the current.

So (*a*) and (*b*) together are equivalent to a fixed impedance in series with each phase winding. Usually the effect of resistance is sufficiently small to be neglected.

(*c*) Magnetic fluxes produced by the armature currents and passing into the main field magnets modify the main field and affect the generated e.m.f. The precise effect depends on the phase angle of the armature currents.

If there is no phase difference between the current and the e.m.f. due to the *original undisturbed field*, there will be a band of currents in conductors centrally opposite the poles. These currents produce magnetic fluxes across the pole shoes from tip to tip, without passing down the poles. The result is a distortion of the main field without direct weakening or strengthening.

If, on the other hand, the currents lag by some angle, the current bands lag to a corresponding extent behind pole centres. Some of the magnetic flux produced then passes down the main poles in opposition to the original field and weakens it. For similar reasons a leading current strengthens the main field.

In general, then, a load with a lagging power factor results in a reduction of the generated e.m.f. due to the weakening of the field, whereas a leading power-factor load has the reverse effect, and may actually raise the terminal voltage.

The combined effects of (*a*), (*b*) and (*c*) are equivalent to those of a fictitious impedance, called the *synchronous impedance.*

The effects of the synchronous impedance on the terminal voltage depend both on the load current and the load power factor.

Varying Voltage

When a balanced load is gradually applied, and the exciting current is kept constant, the terminal voltage varies in the manner shown by the curves of Fig. 23.

Normally, the voltage falls as the load comes on, but when the P.F. is a leading one the load characteristic curve may rise at first. Each graph is nearly straight at the beginning but tends to droop because, as the load rises, the angle of lag between current and e.m.f., due to the original field, increases. The curves shown are for three definite power factors as indicated.

The highest current is obtained when the alternator terminals are short-circuited, the value being $I_s = \frac{V_0}{Z_s}$ amperes, where V_0 is the no-load voltage, and Z_s the synchronous impedance. All curves meet at the short-circuit point.

In modern alternators, the steady short-circuit current is not much greater than the normal full-load current. This is purposely arranged to prevent excessive current in the event of a short-circuit. The synchronous impedance $Z_s = \frac{V_0}{I_s}$ can be found from measurements of open-circuit volts and short-circuit current for the same excitation.

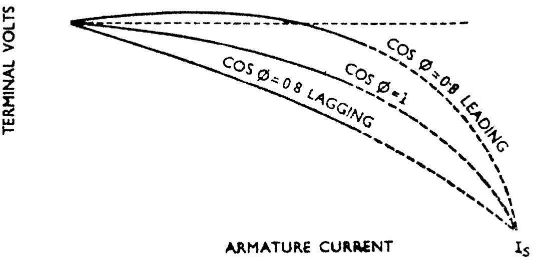


Fig. 23. Load characteristics of an alternator. The change of terminal voltage with load current is brought about by the effects of synchronous impedance and depends on the load power factor. Owing to the demagnetizing effect of lagging current, the voltage falls most steeply with low-lagging power-factor load. On the other hand, a leading current has a magnetizing effect, and raises the terminal voltage at first as the load increases. The reason why this rise does not continue is that even though the *load* power factor may be a leading one, when the current is large it may actually lag behind the e.m.f. due to the main field. In other words, the synchronous reactance of the machine determines the *internal* phase angle. The short-circuit current I_s is equal to $\frac{V_0}{Z_s}$ amps, where V_0 is the no-load voltage and Z_s the synchronous impedance. The synchronous impedance can be found by dividing the open-circuit voltage by the short-circuit current with the same exciting current in each case.

The "regulation" of an alternator is the *rise* of terminal voltage which occurs when the full load is switched off and depends on the power factor. It is usually expressed as a percentage of the normal voltage, and can be obtained from the vector diagram or by actual measurement.

As every change of load brings a change of voltage, some means must be provided for adjusting the excitation continuously in order to maintain constant voltage. This is done by means of automatic voltage regulators which operate on the exciting current. They are controlled by suitable relays and are designed to give rapid action to prevent voltage fluctuations.

In a generating station, two or more alternators frequently operate in parallel and share the load. When the demand is low, for instance in the small hours of the morning, possibly only one machine will be running, but as the load increases at the beginning of the day it becomes necessary to start up an additional machine, parallel it with that already running, and make the necessary adjustments for the proper sharing of the load.

Alternators in Parallel

Before the new or incoming alternator can be paralleled with one or more already running on load, the following conditions must be fulfilled:

(*a*) Its R.M.S. voltage must be equal to the voltage of the bus-bars to which it is to be connected.

(*b*) Its frequency must be the same as that of the running machines.

(*c*) The corresponding voltages of the incoming and running machines must be in phase. The correct phase sequence is attended to when the machines are first installed in position.

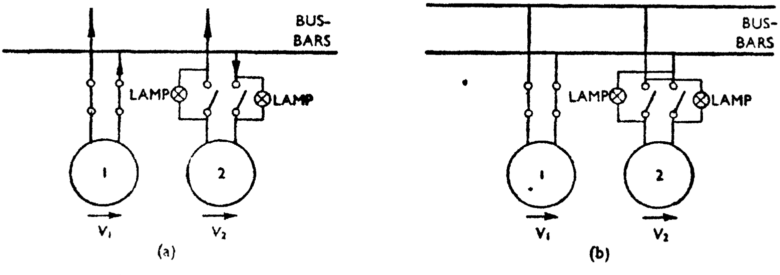
The procedure for bringing in a new machine is as follows. First, the speed is brought up to approximately the correct value by the aid of the engine-room tachometer or speed indicator. Next, the excitation is applied and the voltage is adjusted until equal to the bus-bar voltage. The speed is then further adjusted by operating on the engine or turbine governor until there is practically no frequency difference between the two systems. This is indicated by a special device which will be described in a moment.

With very slight frequency difference, the new machine comes gradually into phase, and if the paralleling switch is closed when there is no phase difference, no jolt or disturbance of any sort occurs on the system.

Synchronizing

The process of bringing two alternators to the same frequency and into phase is called *synchronizing*. A special instrument, known as a *synchroscope*, is used for the purpose, but the mechanism of synchronizing is best illustrated by a simple method using two lamps connected across the paralleling switch as shown in Fig. 24.

Single-phase machines are shown for simplicity. When they are in phase their voltages, acting round the *local circuit* of Fig. 24a, are opposed to each other and no



SIMPLE MECHANISM USED FOR SYNCHRONIZING

Fig. 24. Using synchronizing lamps, dark (a) and bright (b), when the machines are in phase. In either case, one lamp can be replaced by a voltmeter and the other replaced by a resistance equal to that of the voltmeter.

current flows through the lamps, which are, therefore, dark. As the machines get out of phase, the vector difference of their voltages occurs across the lamps, which glow at their brightest when the machines are fully out of phase.

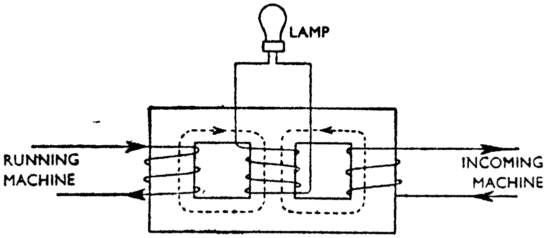


Fig. 25. Synchronizing transformer for use where the machine voltages are too large to allow synchronizing lamps or voltmeters to be utilized directly. When the machines are in phase the primary windings drive their fluxes in opposite directions round the outer core and so down the central limb.

The lamps, therefore, brighten and darken at a frequency equal to the difference between the frequencies of the two machines. The switch must be closed at the middle of a dark period. As it is rather difficult to determine accurately the middle of a dark period, the arrangement of Fig. 24b is better. Here, the lamps are brightest when the machines are in phase.

Synchronizing Equipment

With high-voltage machines, lamps cannot be used in this way and a special synchronizing transformer, as illustrated in Fig. 25, is necessary. It is connected so that the brightest glow of the lamp indicates the in-phase condition.

Special synchronizing equipment is installed in a generating station. This comprises a panel containing the two necessary voltmeters, the synchroscope, and indicating lamp. A typical synchronizing system is illustrated in Fig. 26. The synchroscope has a rotor whose speed is exactly equal to the frequency difference of the two systems and carries a pointer indicating the phase difference at every instant. The machines are in phase when the pointer is vertically upwards. The main switch should be closed just before the in-phase position with the incoming machine running very slightly fast.

Once the alternators are in parallel, as in Fig. 27a, they will hold each other in step, due to the effects of armature reaction. If the voltages are equal but slightly out of step when the switch is closed, as indicated by the vector diagram of Fig. 27b, the vector difference voltage $V_1 - V_2$ drives a circulating current I_0, nearly 90 deg. behind $V_1 - V_2$, round the local circuit through the two machines. This is nearly in phase with V_1 of the leading machine, representing a power output of approximately $V_1 I_0$, and nearly in *antiphase* with V_2 of the lagging machine, which *absorbs* power $V_2 I_0$.

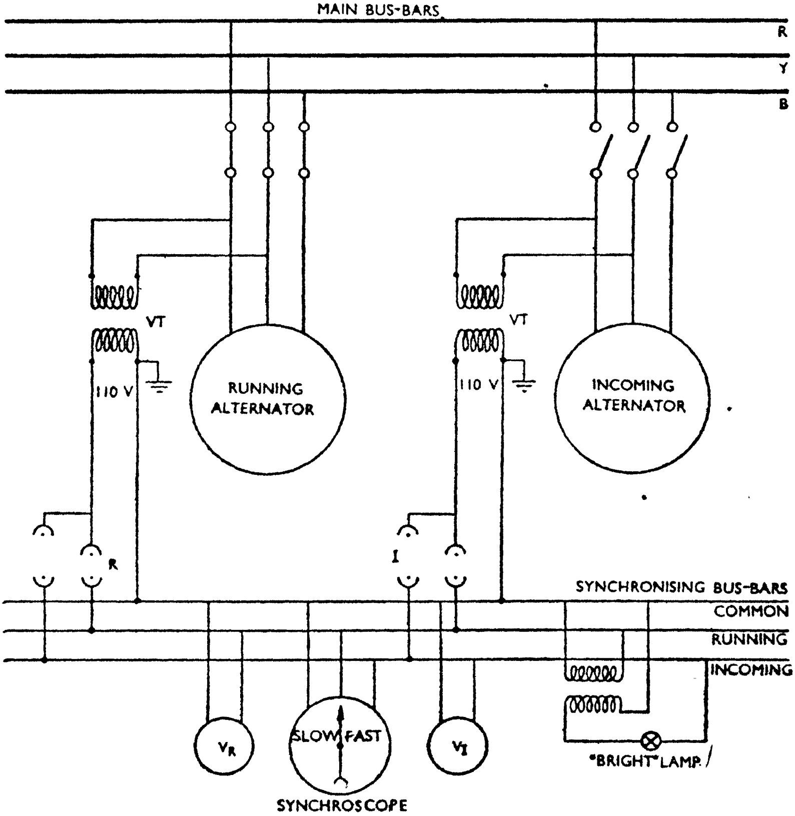
Self-correcting Effect

The lagging machine, therefore, acts as a motor temporarily, and is accelerated. It will pull into phase but will overshoot the central position, conditions being reversed.

The tendency for continuous oscillation or *phase-swinging* about the in-phase position is damped out by induced currents in the rotor core or in special damping bars embedded in the pole faces and riveted to end plates. The synchronizing force produced by the current I_0 is nearly proportional to the phase displacement and so the machines are held together as though they are coupled through an elastic or spring coupling.

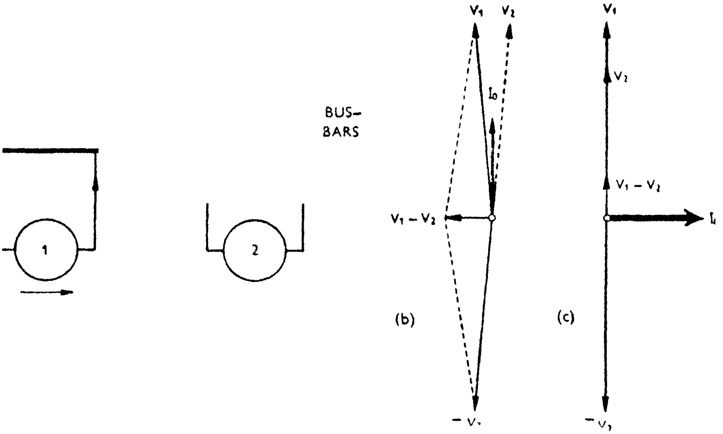
On the other hand, suppose that the machines are paralleled when the terminal voltages are in phase but slightly unequal. These conditions are shown by Fig. 27c, where V_1 is larger than V_2. The circulating current I_0 will now lag nearly 90 deg. behind V_1 and lead V_2 by nearly 90 deg.

So, through armature reaction, machine 1 with the larger voltage



TYPICAL SYNCHRONIZING SYSTEM USED IN GENERATING STATIONS

Fig. 26. Synchronizing instruments are mounted on a panel in a convenient position relative to the main switchboard and are permanently connected to the three "synchronizing bus-bars" as shown. The "running" and "incoming" machines are connected to the corresponding bus-bars by the insertion of two-pin plugs *I* and *R*, each of a different gauge, in the appropriate sockets. By having only one plug of each gauge available, there is no danger of plugging both machines on to the same bus-bar. All instruments are operated from the low-voltage sides of voltage transformers *VT*, the common secondary terminals being taken to earth.



ILLUSTRATING SELF-CORRECTING EFFECTS

Fig. 27. These arise when two alternators are paralleled at an instant when the ideal conditions are not fully satisfied. The local circuit after paralleling is represented at (a). When the voltages V_1 and V_2 are in phase with respect to the bus-bars, they are in phase opposition round the local circuit formed by the two machines and the bus-bars. The vectors here refer to the bus-bars. At (b) and (c) are the vector diagrams showing the conditions which arise if the machines are paralleled on the one hand with voltages equal but slightly out of phase, and on the other with the voltages in phase but slightly unequal.

undergoes demagnetization, and machine 2 with the smaller e.m.f. has its field strengthened. In this way the inequality of voltages is automatically corrected, I_0 having a value which is just sufficient to maintain equality of the terminal voltages.

The kilowatt output of an alternator depends only on the mechanical power given to it by its prime mover and on its efficiency. As the efficiency is nearly constant over normal load variations, we may say that the output depends alone on the mechanical input, which in turn depends on the amount of steam admitted to the turbine by the governor.

Therefore, when two or more alternators are operating in parallel they share the total kilowatt load in approximately direct proportion to the respective steam inputs. This means that load sharing is determined entirely by the governor settings. Variation of excitation does not affect the division of the load as for D.C. generators in parallel.

The power factor of the *total load* is determined by the nature of the load itself and nothing whatever can be done at the generating station to change it.

Power-factor Control

But if the load is shared by two or more alternators, you will find that the power factors of the loads on *each* may differ, and can be controlled. This is done by adjusting the exciting currents of the various machines.

For simplicity, let us suppose there are two identical alternators sharing *equally* a load whose power factor is cos ϕ. The vector diagram for the total load, for one phase, is given in Fig. 28a.

Now, if both machines have exactly the same excitation it will be found that their currents I_1 and I_2 will be equal and in phase. since the conditions are identical for both.

As the total current I is the vector sum of I_1 and I_2, it follows that both I_1 and I_2 must be in phase with the total load current I, as shown in Fig. 28b. Each machine, therefore, operates at the power factor of the total load.

Maintaining Voltage

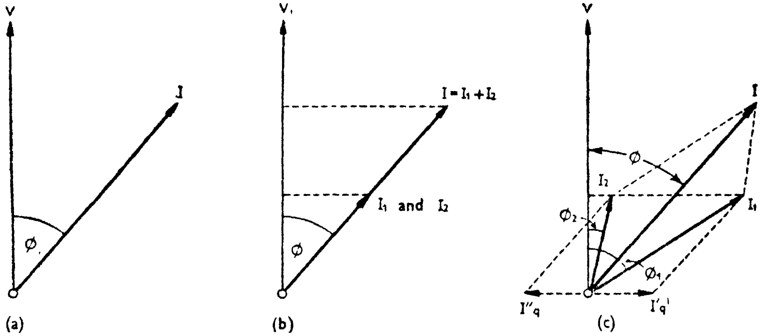
Now, suppose that the excitation of the first machine is increased and that of the second decreased by equal amounts, so that the normal voltage is maintained at the original value V.

The fact that the voltage is unchanged means that in neither machine has the effective field strength altered, despite the changes of exciting current.

What actually happens is that the machine with the increased excitation automatically produces a lagging wattless current I_q just sufficient to off-set the excess excitation, through the action of armature reaction. It will be remembered that a lagging current has a demagnetizing effect on the main field.

On the other hand, the machine with the decreased exciting current produces a leading wattless current I_q just sufficient, through its magnetizing effect, to maintain the main field strength unchanged. The conditions are shown in Fig. 28c, where $\cos \phi_1$ and $\cos \phi_2$ are the power factors of the loads carried by the individual machines.

In general, then, variation of relative excitations results in changes of wattless current and, therefore, of reactive kVA, without



LOADS CARRIED BY INDIVIDUAL MACHINES

Fig. 28. Power-factor control of alternators running in parallel. (a) Vector diagram of the total load whose power factor is cos ϕ. (b) Conditions when each alternator has the same exciting current and takes an equal share of the load. The machines are assumed to be identical. (c) The effect of increasing the excitation of one machine and decreasing that of the other by equal amounts. The load sharing is not affected, each still having the same power component of current, but the wattless components are increased and decreased by equal amounts in the respective machines The power factors are, therefore, changed in the manner indicated. The power factor of the total load is not in any way affected.

affecting the sharing of the kW load or power. It is usually advisable to adjust the exciting currents so that all machines in parallel operate at or near the power factor of the total load, as this makes the total heating losses a minimum. The voltage is controlled by varying the excitation of *all* machines, up or down as required; this being done automatically by the voltage regulator.

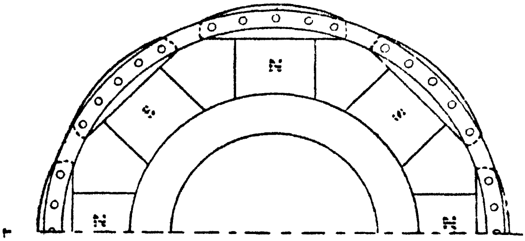


Fig. 29. Illustrating how a "squirrel cage" is built into the field system of a synchronous motor to make it self-starting. The rotating field produced by the stator currents induces e.m.f.'s in the copper bars embedded in the pole shoes. These bars are riveted to rings at each end and the induced currents cause the machine to accelerate by induction motor action. The field poles are excited when the speed approaches that of the stator field, and the rotor pulls into step.

Synchronous Motors

We have seen how two alternators in parallel hold each other in step. If the power supply to one of them is entirely cut off, say, by shutting off the steam to the turbine, that machine will continue to run, *as a motor*. It takes its power from the other machine and keeps in step or in synchronism with it.

A synchronous motor is basically the same as an alternator, but the direction of power is reversed. The stator takes electrical power from the supply, and mechanical power can be taken from the shaft for driving other machinery. As in the case of an alternator, the main field is produced by direct current and the necessary exciter is usually built on to the motor shaft.

Leaving the question of starting for the moment, let us consider a synchronous motor running unloaded from a constant voltage three-phase supply.

In the motor, three-phase currents are driven through the armature windings by the supply voltages, and they produce a rotating field which moves round the stator core with constant speed equal to $\frac{60f}{p}$ r.p.m., where f is the supply frequency and p the number of pole pairs.

Each N pole of the rotor is attracted by a S pole of the armature field and is pulled round with it. And each S pole of the rotor is pulled round by a N pole of the stator field. The two fields become interlocked and the rotor revolves at exactly the same speed as the rotating field produced by the armature currents. Therefore, it follows that the motor runs at "synchronous speed."

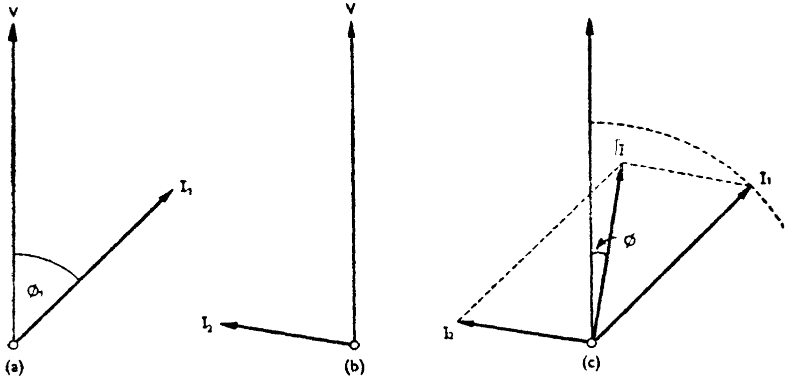
Starting Synchronous Motors

Until the two fields are locked together in this way they will not exert any continuous pull on each other and, for this reason, it is necessary to run a synchronous motor up to speed and synchronize it before it will act.

In other words, it is not a self-starting motor, and the necessary accelerating torque has to be got by some other outside means.

A small auxiliary induction motor with one pair of poles less than the main motor, mounted on the same shaft, can be used for the purpose. But it is usual for modern three-phase synchronous motors to have a *squirrel cage* (like that of an induction motor), built into the pole shoes.

This consists of a number of copper bars through the pole shoes, like the damping bars of an alternator, but riveted into *complete* copper rings at each end. The arrangement is illustrated in Fig. 29.



SYNCHRONOUS CONDENSER VECTORS

Fig. 30. Vector diagrams showing how a synchronous condenser raises the power factor of the load on a system when put in parallel with a load of low-lagging power factor. (a) Vector diagram of original load—current I_1 and power factor $\cos \phi_1$. (b) Vectors for synchronous condenser alone, when over-excited to operate at a low leading power factor. (c) Combined diagram for load and synchronous condenser in parallel. The total current taken is I, the vector sum of I_1 and I_2, and is nearly in phase with V. The power factor is, therefore, near unity in this case. The new current I on the system is actually less than the original current I_1.

Phase-swinging Prevented

To start the machine, three-phase currents are applied to the stator windings with the main poles unexcited. It starts up as a squirrel-cage induction motor and reaches a speed just below synchronism. The exciting current is then applied and rotor pulls into step with rotating field of stator.

This arrangement avoids the need for synchronizing gear and the squirrel cage provides the necessary damping for the prevention of phase-swinging.

Determination of Speed

At the synchronous speed, the cage revolves at the same speed as the stator field and has no currents induced in it. Only in the event of a tendency for change of speed, as in phase-swinging, are currents induced in it and these check the change by their magnetic effect.

The speed of a synchronous motor is determined entirely by the frequency of the supply, and its terminal voltage is equal to that of the supply. So variation of exciting current changes neither the voltage nor the speed. This means that the generated back e.m.f., and the flux per pole, therefore, are practically constant and independent of the exciting current.

The effect is quite unlike that in a D.C. motor, where change of exciting current changes the field strength and alters the speed. In the synchronous motor, a change of excitation brings about a change of wattless current in the stator just sufficient, through the action of armature reaction, to maintain the field strength unchanged.

A current lagging 90 deg. behind the generated (back) e.m.f. and, therefore, *leading the applied voltage*, has a demagnetizing effect, and vice versa. An increase of excitation causes the machine to take extra leading wattless current or less lagging wattless current. Similarly, a decrease of excitation increases the lagging component of current taken.

With constant power input, that is, with constant h.p. output approximately, the power component or in-phase component of current remains unchanged when the excitation is varied. We see, then, that change of excitation alters the power factor at which the machine operates.

Leading Power Factor

The *normal* field current is that which gives the correct field strength without any wattless current in the armature windings, and with which the motor, therefore, operates at unity power factor. An increase of excitation above this value brings into being a wattless leading component of current in the armature windings and *the machine operates with a leading power factor.*

This is a valuable property which is turned to account in power engineering, the chief application being power factor improvement of loads with normally low lagging power factors. If an over-excited synchronous motor is put in parallel with such a load, its leading wattless current partly or completely neutralizes the lagging wattless current of the original load and so raises the overall power factor.

The degree of correction obtained depends on the degree of excess excitation of the synchronous motor. Vector diagrams showing the effect are given in Fig. 30.

Synchronous Condenser

Used in this way, the synchronous machine acts like a large variable capacitance in parallel with a fixed resistance, the latter representing the losses in the machine. It is called a *synchronous condenser*, and is specially designed for the purpose; the field winding having ample current-carrying capacity to permit continuous running with the exciting current 100 per cent above the "normal" or unity P.F. value.

A synchronous condenser runs light, being unloaded mechanically. The power wasted in losses is more than compensated for by the advantages gained in the improved power factor of the load on the system.

As suggested, such a relatively expensive apparatus is employed where power factor correction on a large scale is necessary. In most situations, correction by the connection of condensers, as fully explained at the end of the previous chapter, is all that is necessary.

We can now turn, in the next chapter, to a study of the types of motor designed to operate from alternating-current supplies.

CHAPTER 9

INDUCTION AND A.C. COMMUTATOR MOTORS

GENERAL FORM OF MOTOR. PRINCIPLE OF OPERATION. EFFECT OF ROTATING FIELD. SLIP AND TORQUE. STARTING ARRANGEMENTS. SQUIRREL-CAGE MOTORS. SLIP-RING TYPES. SINGLE-PHASE INDUCTION, SPLIT-PHASE AND CAPACITOR MOTORS. A.C. COMMUTATOR MOTORS. SINGLE-PHASE SERIES MOTOR. THREE-PHASE SERIES AND SHUNT MOTORS. CHOOSING AN A.C. MOTOR.

BY far the greater part of all the mechanical power used in industry is provided by three-phase induction motors. The reason is that the induction type is the simplest and least expensive. It is a robust machine requiring a minimum of maintenance.

An outstanding feature of the induction motor is that under running conditions no electrical connection is required to the rotating part or *rotor*. Currents are *induced* in the rotor circuits by electromagnetic induction. There is one widely used form with slip-rings and brushes, but these parts are employed only for starting; during normal running the brushes are lifted from the slip-rings, which are simultaneously short-circuited by a mechanical device.

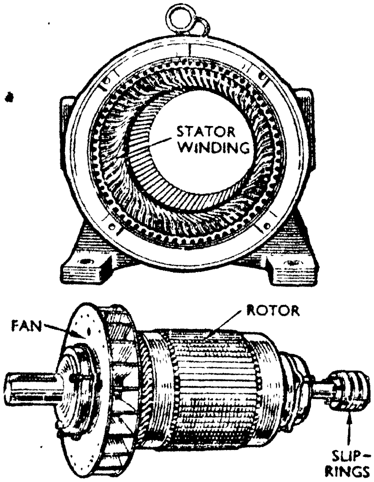


Fig. 1. Stator and rotor of a three-phase slip-ring induction motor. Ball or roller bearings, which are not visible, are contained in housings on the shaft.

Absence of Friction

With the induction motor there is, therefore, a remarkable absence of friction, especially in modern machines with ball or roller bearings, and the efficiency is good. The chief disadvantages are that the power factor is low, especially at light loads, and speed control is not easy to achieve. Normally, the speed falls slightly as the load is increased, in much the same way as that of a shunt-wound D.C. motor.

Except for small machines, induction motors are nearly always of the three-phase type. As two-phase supply is now rare, two-phase motors are few, but their characteristics are the same as those of the three-phase machine. There is a single-phase type, but this will be easier to understand when we know something about the action of the three-phase motor, which, therefore, will be considered first.

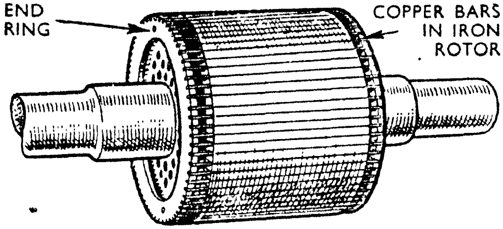


Fig. 3. Squirrel-cage rotor. The copper bars protruding from the slots are sweated into massive rings at either end of the rotor. The slots themselves are slightly askew to promote smooth running and to minimize magnetic hum.

The motor comprises two main parts, the *stator* or stationary part, and the *rotor* or rotating part. The stator is constructed in the same way as for a stationary-armature alternator, and, as seen in Fig. 1, carries a similar three-phase winding.

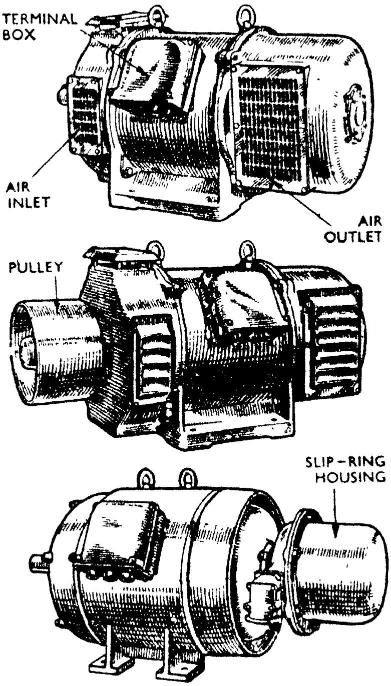


Fig. 2. Slip-ring induction motors. (Top) Screen-protected with internal slip-rings. (Centre) Drip-proof motor with louvred covers over the ventilating apertures. (Bottom) Totally enclosed fan-cooled motor with slip-rings in special housing. This type is used where there is much dust in the atmosphere and where pipe ventilation is impracticable.

The outer frame or casing supporting the laminated stator core may differ in appearance from that of an alternator, since it is designed specially to suit the conditions under which the motor operates. For instance, a motor installed in a dry, dust-free situation can have an open-type frame or be provided with open ventilating apertures, whereas a unit which has to operate in the open or in a wet situation, or where there is much dust, would be totally enclosed with, perhaps, pipe ventilation or with cooling fins cast on the outside of the frame or carcase. Three different forms of housing are shown in Fig. 2.

Two Forms of Rotor

The rotor comprises a cylindrical laminated iron core, much the same as that of a D.C. machine, with slots for carrying the rotor conductors. There are two main forms of rotor, according to the nature of the "winding."

In one there is a single copper or aluminium bar in each slot and all these bars are joined at each end to

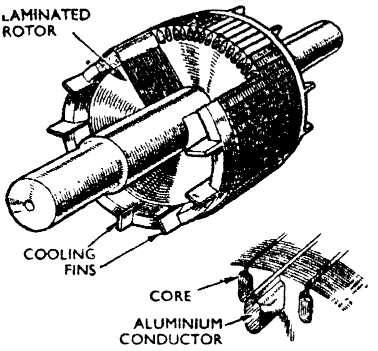


Fig. 4. Cut-away view of squirrel-cage rotor in which rotor bars, end-rings and cooling fins are of aluminium alloy cast in one piece. There are no joints and the rotor is virtually indestructible.

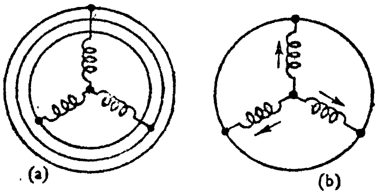


Fig. 6. Basic circuit of slip-ring rotor. (a) With slip-rings on open circuit. (b) Equivalent circuit when all three rings are short-circuited. The arrows indicate the directions of the currents when they are positive, but they are three-phase currents and, therefore, never all positive at the same time.

massive end rings, so forming a "squirrel cage." This is known as the squirrel-cage rotor (Fig. 3).

As all the bars are joined at the ends, there is no need for any electrical insulation, and bare conductors may be embedded in the slots. The cut-away drawing, Fig. 4, portrays this. The squirrel cage itself may be constructed with copper bars silver-soldered into grooves in the end rings (soft solder would melt in the event of the rotor becoming overheated by any accidental overloading), or the rotor bars and end rings may be of aluminium, cast in one piece.

Alternative Rotor

The other form of rotor has an ordinary three-phase winding consisting of insulated coils like those of an alternator of the rotating armature type. A sectional diagram of such a motor is given in Fig. 5. The three phases are star-connected, the free ends being joined to three slip-rings mounted on the

the motor is running, the slip-rings are short-circuited, giving a closed-circuit effect much like that of the squirrel-cage type. As we proceed we shall learn why slip-rings are used and how currents are induced into the short-circuited rotor circuits. Completed rotors of both wound and

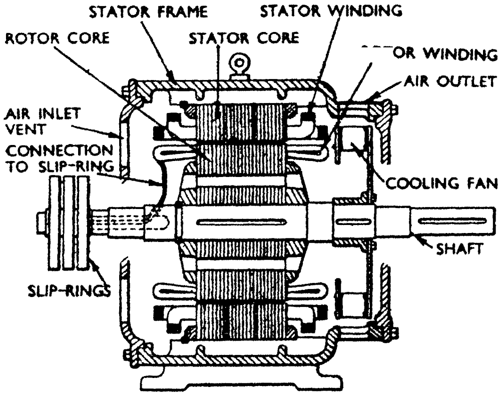


Fig. 5. Section of an induction motor of the slip-ring type showing the main features. A roller bearing would be used at the pulley end, and at the slip-ring end either a ball bearing or a combination of roller and ball bearings.

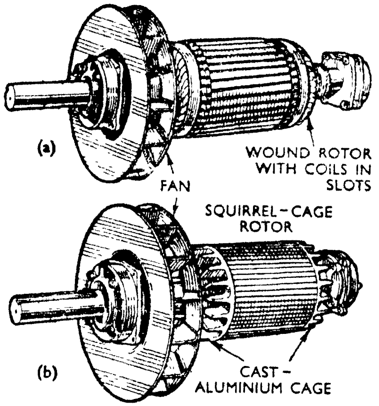


Fig. 7. (a) Wound rotor of slip-ring motor. (b) Squirrel-cage rotor with cast-aluminium cage. The stator for each is identical in all respects.

squirrel-cage types are shown in Fig. 7.

The action of the induction motor depends on the production of a rotating magnetic field of constant strength by three-phase currents in the stator windings. This rotating field "cuts" the short-circuited rotor conductors—providing they are not rotating at the same speed as the rotating field—and induces e.m.f.'s in them.

The resulting currents in the rotor conductors produce their own magnetic fluxes and these interact with the main rotating field and set up forces on the conductors in the direction of rotation of the stator field.

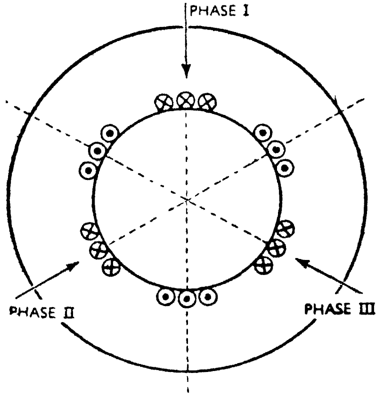


Fig. 8. Stator core with groups of conductors of a three-phase winding. The dots and crosses indicate the positive directions of the currents.

Rotating Magnetic Field

Let us look into all this more closely. First, how is a rotating field produced by three-phase currents in the stator winding?

Fig. 8 represents a simplified stator core with three equally spaced phase windings. Normally, the conductors are evenly spread round the core, but they are here shown in separate groups to enable the individual phases to be distinguished. The dots and crosses show the directions of the currents in the conductors *when they are positive*. (But, of course, they are never all positive at the same time, nor are they ever all equal at any one time.)

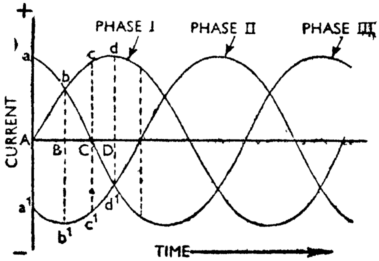


Fig. 9. Curves showing how the three-phase currents vary with time.

Phase Relationship

In Fig. 9 is shown the phase relationship of the currents applied to the rotor. We see that at instant *A*, for example, current in Phase I is zero, current in Phase II is negative

(Aa^1, about 87 per cent of peak value), and that in Phase III is positive (Aa, also about 87 per cent of peak value).

The directions of currents in the conductors at instant *A* are indicated in Fig. 10a. Phase I has no current. Phase II has negative current, so the signs are reversed compared with Fig. 8. Phase III has positive current, the signs being the same as in Fig. 8.

Rotation of Field

So at instant *A* all the currents on the left of the stator are towards us (dots), and on the right away from us (crosses). The field produced by them is, therefore, vertically upwards as shown.

At instant *B* in Fig. 9, one-twelfth of a cycle later, Phases I and III have positive currents and Phase II negative current. The conditions are shown at (b) in Fig. 10. Resulting field is seen to have changed direction by 30 deg.

The conditions for instants *C* and *D* are similarly represented in Fig. 10c and (d). We see that during each twelfth of a cycle the field rotates through 30 deg., or one-twelfth of a revolution. So, during a whole cycle the field revolves through 12 × 30 = 360 deg., or one revolution. This is for a 2-pole field and, therefore, if the frequency is *f* cycles per second, the field rotates with a speed of *f* r.p.s.

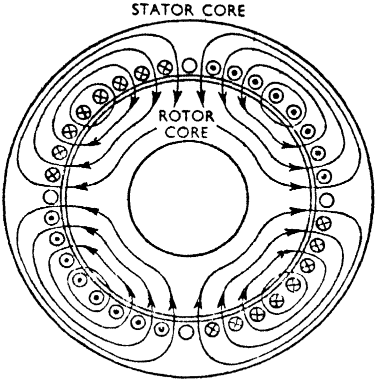
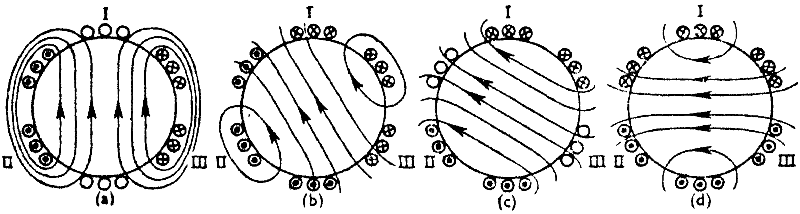


Fig. 11. Nature of magnetic field produced by a three-phase 4-pole winding. Groups of magnetic flux rotate round stator core at constant speed of f/p revs. per sec., where f = frequency and p = number of pairs of poles (in this case two). At 50 cycles, field speed is 3000 r.p.m. for 2-pole machine, 1500 for 4-pole, 1000 for 6-pole, and 750 for 8-pole.

Rotating Fluxes

The nature of the rotating fluxes in a 4-pole three-phase machine is shown in Fig. 11. With a 4-pole winding it can be shown that the field makes half a revolution per



POSITIVE CURRENTS FOR 2-POLE FIELD

Fig. 10. Diagrams showing the actual directions of currents at various instants, and the magnetic fields which have been produced by them. (a), (b), (c) and (d) correspond to the instants *A*, *B*, *C* and *D* respectively in Fig. 9. The field as a whole is seen to be rotating, making one revolution during each cycle of current.

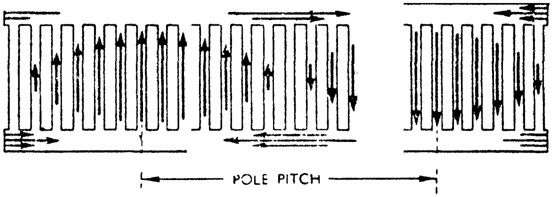


Fig. 13. Diagram showing a squirrel-cage "winding" opened out into a flat surface. The arrows indicate the currents at a particular instant. The currents are greatest in those bars opposite pole centres, whereas the currents in the rings are greatest at points midway between poles.

cycle. In general, then, if the winding produces p pairs of poles, the stator field speed is

$$n_1 = \frac{f}{p} \text{ revs. per sec.}$$

Now, what is the effect of this rotating field on the rotor of the machine? In the first place, suppose that the rotor is stationary and locked and cannot rotate.

Induced e.m.f.

The rotating field of the stator passes through the rotor core and cuts the conductors. The diagram of Fig. 12 represents the stationary rotor within the revolving field of a 2-pole stator. To make the diagram simple, the stator core itself is not shown.

As the lines of magnetic flux move across the rotor conductors, the e.m.f. induced in any one conductor is proportional to the field speed and to the field strength where the conductor is. The direction of the e.m.f. is given by Fleming's Right-hand Rule.

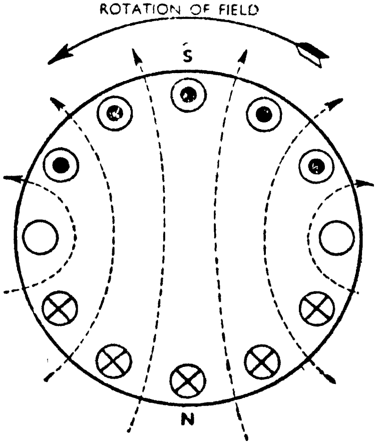


Fig. 12. Diagram showing a rotating field "cutting" the conductors of a stationary rotor. The directions of the induced e.m.f.'s are given by Fleming's Right-hand Rule, and are indicated.

The e.m.f.'s produced in the conductors are alternating and have the same frequency (when the rotor is stationary) as the stator currents, because each conductor is passed by one N and one S pole during each cycle of stator current.

Flowing in Bands

Since the rotor circuits are closed, the induced e.m.f.'s produce currents in them. In the case of the squirrel-cage rotor the currents flow in bands as indicated in Fig. 13, conductors near the pole centres carrying the largest currents. In a wound rotor there are similar current bands, but in this case the conductors form the sides of coils, groups of them in series being joined up or short-circuited at the star point and at the short-circuited slip-rings (Fig. 14).

These rotor circuits are inductive and, therefore, have reactance, which causes the currents to lag behind the e.m.f.'s. (For the moment we shall assume the resistance to be sufficiently high to make the angle of lag negligibly small.) The currents in the conductors are then represented by the same signs (dots and crosses) as the e.m.f.'s in Fig. 12.

Magnetic Effect

Let us single out the uppermost conductor and consider the magnetic effect of the current in it. The field produced by the current takes the form of loops or circles surrounding the conductor.

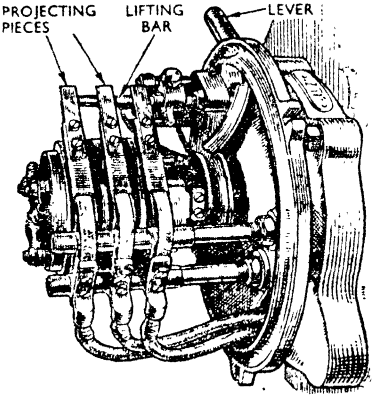


Fig. 14. A centrifugal device on the end [illegible] proaches the normal value. The brushes are lifted manually by the lever. When this is pressed down, the lifting bar, beneath the projecting pieces fixed to the brush holders, rises and lifts the brushes.

In Fig. 15a is shown part of the stator rotating field, undisturbed, with the rotor conductor imagined to have no current. At (b) is the field surrounding the rotor conductor, produced by the current in it; the stator flux is imagined to be absent. The actual conditions are shown at (c), where the two fields of (a) and (b) combine to give the resultant field shown.

Now each line of magnetic flux always tries to take the shortest path—it is as though each line of force were in tension. In trying to straighten out, the lines push the conductor to the left; that is, in the direction in which the stator field is moving.

Here we have a visual indication why the rotating field exerts a pull on the rotor.

The direction of force on any conductor may be found by applying Fleming's Left-hand Rule. The forefinger will indicate the direction of the flux, the second finger the current in the conductor, and the thumb the *force* (being the strongest digit). The average force on all the conductors is in the direction of the rotating field, in this case anti-clockwise.

If the rotor is free to revolve, it speeds up in the direction of the rotating field. But when this happens the field cuts across a conductor at a slower rate. Each pole of the stator field takes a longer time to pass the rotor conductor.

So both the e.m.f.'s and the frequency in the rotor circuits be-

Rotor Acceleration

If the rotor continued to accelerate until eventually its speed became equal to that of the stator field, the conductors would be moving at the same speed as the magnetic flux, there would be no cutting of the lines of force and no e.m.f.'s or currents in the rotor circuits.

As there must always be some frictional and other losses, however, this condition of synchronous speed can never be quite reached, even with the motor unloaded. There is always a degree of "slip" between the stator field and the rotor.

Under load, a motor runs at a speed just sufficiently less than the field or "synchronous speed" to give the required rotor current and driving torque. Slip, therefore, is a factor of major importance whenever we are studying the characteristics of a motor.

Slip Speed

Suppose the synchronous speed to be n_1. We have seen that $n_1 = \frac{f}{p}$ revolutions per second. If n_2 is the speed of the rotor, the difference between the speeds of the stator field and the rotor itself is $n_1 - n_2$.

This relative speed is called the *slip speed* and is equal to some fraction of the field speed n_1. This fraction is called the *fractional slip* (s), or merely the slip. Sometimes the slip is expressed as a percentage of the field speed. The slip is, therefore,

$$s = \frac{n_1 - n_2}{n_1}$$

from which,

Slip speed, $n_1 - n_2 = sn_1$

and,

Shaft speed, $n_2 = n_1(1 - s)$

revs. per sec.

If f is the supply frequency, the rotor frequency is sf.

As an example, a 6-pole 50-cycle induction motor runs at 950 r.p.m. at full load. What is the slip ?

There are three pairs of poles, so the synchronous speed is

$$n_1 = \frac{f}{p} = \frac{50}{3} \text{ revs. per sec.,}$$

$$= \frac{50 \times 60}{3} = 1000 \text{ r.p.m.}$$

Therefore the slip is given by :—

$$s = \frac{n_1 - n_2}{n_1} = \frac{1000 - 950}{1000} = 0{\cdot}05,$$

or 5 per cent, and the rotor frequency is, $sf = 0{\cdot}05 \times 50$

$= 2{\cdot}5$ c.p.s.

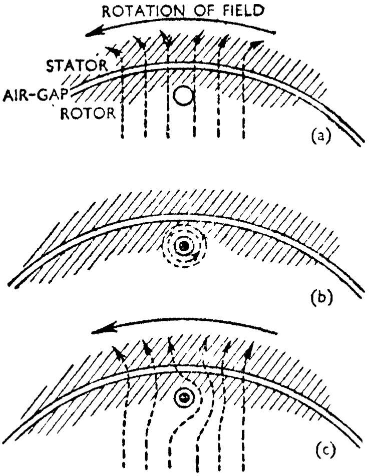


Fig. 15. Diagram showing how and why a rotational force is produced on the rotor by the rotating field of the stator. (a) Part of stator field in which a rotor conductor is imagined to have no current. (b) Field produced by current in rotor conductor, with stator flux imagined absent. (c) Combined effect of the two fields (a) and (b) superimposed.

There is a definite relationship between the slip (or the speed) and the torque exerted on the rotor. Changes of speed brought about by the application of different loads are accompanied by current changes in both rotor and stator circuits, changes both in magnitude and phase angle relative to the applied stator voltage.

Torque and Slip

Assuming constant strength of rotating field, the torque is proportional to the *power component* of the rotor current per phase. At no-load the torque exerted on the rotor is very small and the rotor current is correspondingly small. As the load is increased the rotor current rises and its angle of lag is increased. This is because the rotor frequency rises in proportion to slip.

At first the power component of the rotor current increases but as the load torque is further raised the increasing angle of lag results eventually in a reduction of power component of current, despite the fact that the actual current continues to rise. Maximum torque, therefore, occurs at a definite speed and slip. It can be shown that the maximum torque occurs when the rotor reactance per phase is equal to the resistance.

With the motor stationary the power component of the rotor current is comparatively small.

Resistance Starting

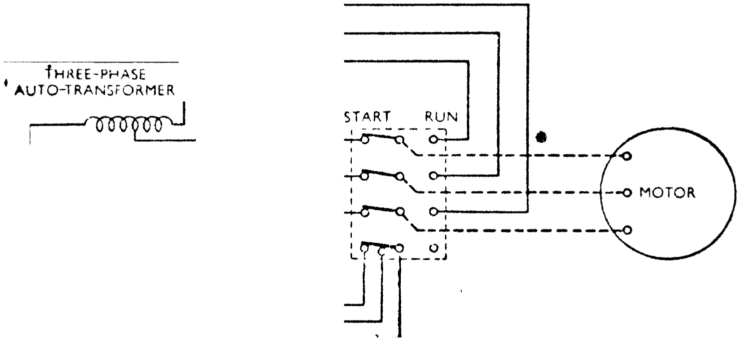
When a motor is running under load, it adjusts itself to that speed at which the slip results in the production of the required torque.

As explained above, the starting torque is small, but the maximum torque can be made to occur at any speed, including zero, or standstill, by making the resistance equal to the reactance *at that speed.* By fitting slip-rings and using a wound rotor, extra resistance can be put in circuit for starting and then cut out as the motor runs up to speed.

In the starting of any type of motor there are two main considerations. Firstly, the starting torque must be sufficiently high to give adequate acceleration, and, secondly, the starting current must not be so high as to cause disturbances on the supply system or to damage the machine itself. Small induction motors from about 2 h.p. downwards can be switched directly on to the mains without fear of disturbance or damage, but for larger motors special arrangements must be made.

In the case of a D.C. motor, series resistance in the main circuit can be used to keep the starting current within the safe limits whilst at the same time maintaining adequate starting torque, but with the induction motor the problem is not so simple.

As we have shown, the starting or standstill torque of an induction motor without resistance added to the rotor circuits is considerably lower than the full-load torque,



AUTO-TRANSFORMER STARTER FOR A SQUIRREL-CAGE MOTOR

Fig. 1[illegible] Auto-transformer starting is effected in two stages, the transformer being cut out altogether when the switch is thrown over to the full voltage position.

and yet the standstill current is several times greater than the full-load current. A squirrel-cage motor is very bad in this respect, as the ratio of resistance to standstill reactance in the rotor is considerably less than in a wound rotor.

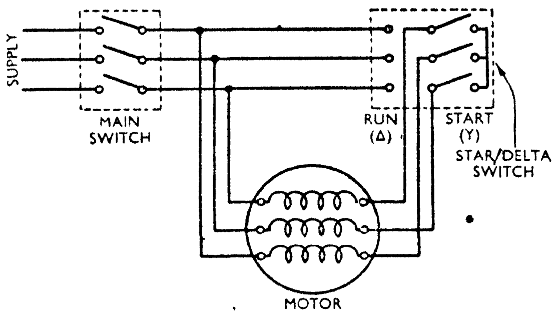


Fig. 17. Star-delta starting of squirrel-cage motor. With star connection, for starting, the voltage applied to each stator phase is $1/\sqrt{3}$ of line voltage. In running position, with mesh or delta connection, full line voltage is applied across each stator phase.

Starting Problems

The problems of starting squirrel-cage and slip-ring motors are quite distinct. In the former, it is not possible to increase the rotor resistance to raise the torque and, to limit the starting current, reduced voltage has to be applied to the stator during starting.

The torque is proportional to the stator field strength and to the power component of the rotor current. As each of these is proportional to the stator voltage, it follows that, by cutting down the applied stator voltage to half the normal value, the starting torque is reduced to a quarter of the already poor value. Hence, a squirrel-cage motor can be started only with no load or under very light load.

There are two practical ways of reducing the applied stator voltage during starting: (*a*) by the use of an auto-transformer; (*b*) in the case of a normal mesh- or delta-connected motor, by starting with the stator windings in star and then changing over to delta connection when the motor has run to speed.

Arrangements for auto-transformer starting are shown in Fig. 16. Starting is effected on the lower voltage tappings and the voltage is increased in two stages as the speed rises. It is usual for the transformer to be cut out altogether after the motor has been started.

Star-delta Starting

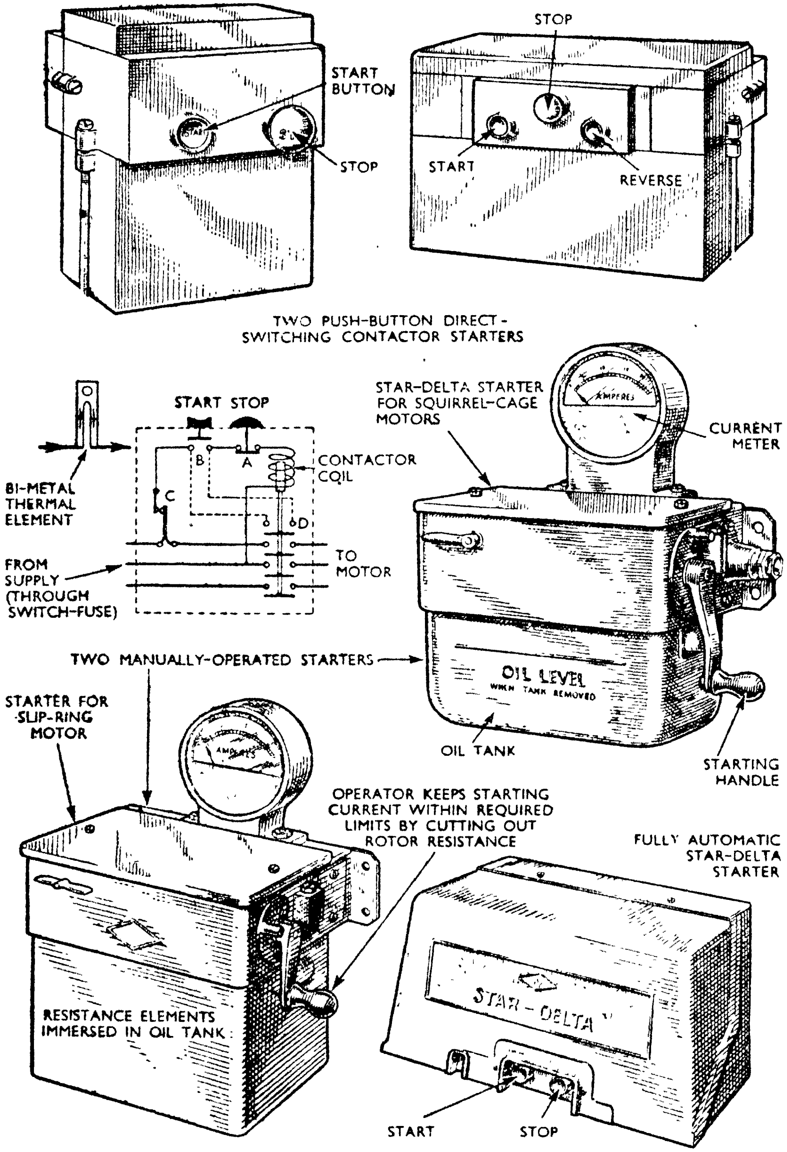
The circuit arrangements for star-delta starting are illustrated in Fig. 17. The six leads to the stator windings are connected to a change-over switch as shown.

With star connection each phase gets $\frac{1}{\sqrt{3}}$ of the line voltage, the starting torque being reduced to one-third.

The modern tendency is to use automatic starters of the push-button type.

On pressing the "start" button the main circuit is closed by a magnetically operated switch called a contactor, the change-over switch being in the "star" position. After a few seconds a thermally operated contact causes the change to be automatically made from star to delta.

If the supply voltage fails with the motor running, the main switch opens as the contactor coil becomes


START BUTTON
STOP
STOP
START
REVERSE
TWO PUSH-BUTTON DIRECT-SWITCHING CONTACTOR STARTERS
START STOP
B
A
CONTACTOR COIL
C
D
BI-METAL THERMAL ELEMENT
FROM SUPPLY (THROUGH SWITCH-FUSE)
TO MOTOR
STAR-DELTA STARTER FOR SQUIRREL-CAGE MOTORS
AMPERES
CURRENT METER
OIL LEVEL
WHEN TANK REMOVED
OIL TANK
STARTING HANDLE
TWO MANUALLY-OPERATED STARTERS
STARTER FOR SLIP-RING MOTOR
AMPERES
OPERATOR KEEPS STARTING CURRENT WITHIN REQUIRED LIMITS BY CUTTING OUT ROTOR RESISTANCE
FULLY AUTOMATIC STAR-DELTA STARTER
RESISTANCE ELEMENTS IMMERSED IN OIL TANK
STAR-DELTA
START
STOP

STARTING COMPONENTS

Fig. 18. (Top, left) Starter for one direction only, and (top, right) a reversing contactor starter. (Centre, left) is the basic circuit of a simple direct-switching contactor starter, with no-load and overload releases; whilst on its right is a manually operated star-delta starter for a squirrel-cage induction motor. (Bottom) Manual starter for a slip-ring motor, and a fully automatic star-delta starter.

de-energized and, at the same time, the change-over switch drops back to the "star" position. All motor starters must be provided with automatic overload and no-voltage release to avoid damage and accidents.

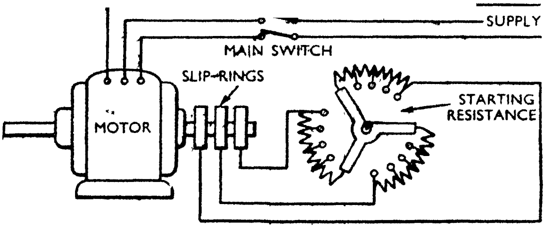


Fig. 19. Starting arrangements of a slip-ring induction motor. The starting resistance is designed to give maximum starting torque and is cut out in steps as the motor accelerates. After starting, the slip-rings are short-circuited internally and the brushes are lifted from the rings. Automatic overload and no-voltage releases are always incorporated in the starting gear to eliminate the possibility of damage and accidents arising, usually by an automatic centrifugal device.

The basic circuit for a direct starting contactor starter is given in Fig. 18. The main switch in the motor circuit is operated by an electromagnet whose actuating coil derives its power from the supply. Normally, the "stop" contact *A* and the overload release contact *C* are closed.

When the "start" button is depressed the contact *B* closes and the contactor coil is connected across one pair of lines.

Main Contacts Closed

The main contacts are closed and, at the same time, the auxiliary contacts at *D* are closed. This short-circuits the contacts at *B*, so that when the "start" button is released and moves back under spring action the contactor coil will remain energized and so keep the main contacts closed.

On pressing the "stop" button, contact *A* opens and interrupts the contactor coil current, allowing the main switch to drop to the "open" position. In the event of an overload, the bi-metal thermal element becomes heated and bends towards the right and opens the contact *C* in the contactor coil circuit.

It is normal practice to have a thermal element in each line to protect the motor against an internal short-circuit between phases or from one phase to earth.

If the supply voltage fails, the main switch drops automatically to the "open" position. Most automatic contactor starters are based on the principle illustrated here, but in some forms the overload release is actuated by an electromagnetic relay instead of the thermal element. Starting components are illustrated in Fig. 18.

Slip-ring Motors

Slip-ring motors are started by introducing resistance into the rotor circuits, with full voltage applied to the stator. We have already seen how the standstill torque is increased by addition of resistance to the rotor circuits. This not only reduces the rotor (and also the stator) current, but at the same time increases the power component of the current.

Most slip-ring motors give a maximum starting torque at least twice as great as the full-load torque and they can, therefore, be started under load. It is mainly for

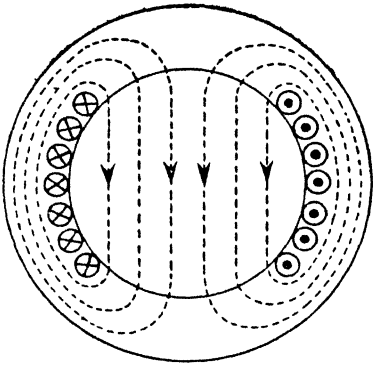


Fig. 20. Single-phase induction motor stator core, showing the arrangement of the conductors and the nature of the field produced. The magnetic field is purely alternating, there being no rotation as there is in the case of a two-phase or a three-phase motor.

this reason that slip-ring motors are made at all, since they are more expensive than squirrel-cage motors.

The arrangements for starting are shown in Fig. 19. The main switch is closed with the starter resistance all in, and this is cut out in steps as the speed rises.

Short-circuited Slip-rings

When the motor is running the slip-rings are short-circuited internally by a mechanical device operated either manually through a lever at the end of the shaft, or automatically by centrifugal force. This is done to cut out the resistance of brushes and contacts; the brushes may then be lifted to reduce frictional losses.

Reversal of rotation is obtained by interchanging the connections to any two terminals on the stator.

Single-phase induction motors are usually small machines, of fractional or low h.p., used on low-power circuits. In the plain motor the stator carries a single winding which produces an alternating, not a rotating, field.

Single-phase Motors

In the arrangement of Fig. 20, the current in the winding produces a magnetic field whose axis is always in the vertical position, but whose strength varies from instant to instant in almost exact proportion to the magnetizing current. It is, therefore, purely alternating.

How is it then that such an alternating flux can produce a rotational torque? Actually, it produces no torque at all on a *stationary* rotor and there is no tendency for

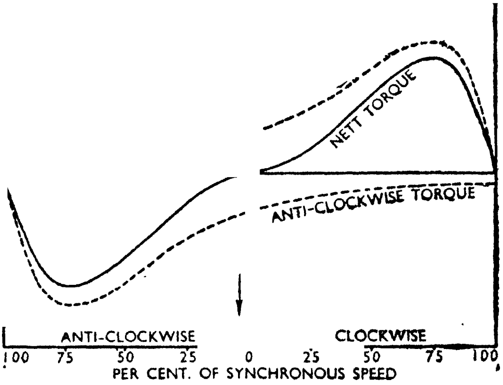


Fig. 21. Torque curve (full line) of a single-phase induction motor. The dotted-line curves are the component torques, acting in opposite directions, due to the two rotating components which go to make up the actual alternating field. The motor will accelerate in the direction in which it is started by hand or otherwise, but is not self-starting; unless fitted with a phase-splitting device.

the motor to start in either direction; but if the rotor is given a start by hand, or otherwise, in either direction, a torque immediately arises (in the direction in which the rotor has been started) and the machine accelerates to full speed.

Two Explanations

There are two ways of explaining this. The simpler is based on the fact that an alternating field is equivalent to the resultant of two constant rotating fields revolving with equal speeds in opposite directions.

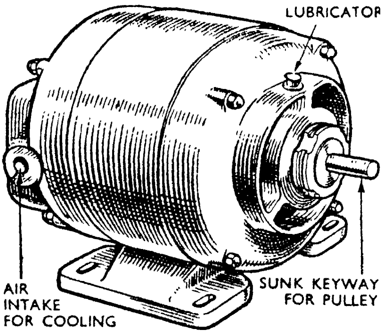


Fig. 23. Illustrating a B.T.H. fractional horse-power split-phase motor.

Now, each rotating component acts on the rotor in precisely the same way as in the three-phase machine; each produces its own torque, but the two torques are in opposite directions, and are represented by the dotted-line curves of Fig. 21. With the rotor stationary they balance and neutralize each other completely.

If the rotor is started by external means, say in the clockwise direction, then the clockwise torque increases whilst the counter clockwise one decreases. There is, thus, a nett torque in the clockwise direction and the motor accelerates. The nett or resultant torque at different speeds is the difference of the individual torques and is indicated by the full-line curve of Fig. 21.

A single-phase motor can be made self-starting by providing the stator with a special auxiliary or starting winding placed electrically at right angles to the main winding as indicated in Fig. 22.

Series Resistance

In series with the starting winding is a resistance *R* to make the angle of lag in it considerably less than that in the main winding. The currents in the two windings then have considerable phase difference and together produce an actual rotating field. The motor, therefore,

one direction and runs up to speed, the starting winding then being cut out of circuit. This type of machine is known as a split-phase motor. To start the motor in the reverse direction it is only

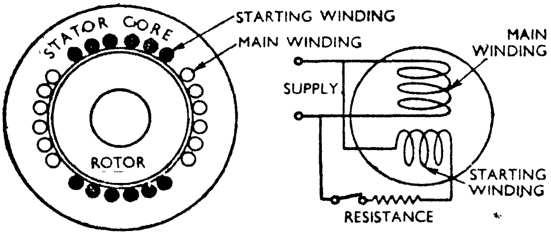


Fig. 22. Split-phase induction motor. An auxiliary starting winding in series with resistance carries a current which is in advance of the current in the main winding. The two produce an actual rotating field which makes the motor self-starting. The starting winding may be cut out of circuit when the motor is running.

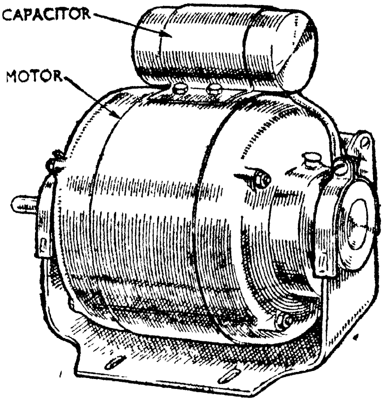


Fig. 24. Small capacitor motor with cylindrical condenser mounted on the motor frame. The condenser plays the double role of improving the starting torque and raising the power factor under running conditions.

necessary to reverse the connections either to the main winding or the starting winding. One of these motors is shown in Fig. 23.

The capacitor motor (Fig 24) is the same in principle as the split-phase motor but is provided with a condenser suitably mounted on the frame. During starting the condenser is put across the resistance in the auxiliary circuit, thereby increasing the phase difference between the currents in the two windings and so increasing the starting torque. With the motor running, the condenser is switched across the main winding to improve the running power factor.

Auto-transformer

In one form the resistance in series with the auxiliary winding is replaced by an auto-transformer across which the condenser is connected. The stepping up of the voltage across the condenser calls for a smaller condenser than would otherwise be required. The circuit arrangement is shown in Fig. 25.

The change over from "start" to "run" position of the switch is effected by centrifugal action when the speed approaches full value, the auxiliary winding being kept in circuit in this form of motor.

Speed-control Difficulties

The plain induction motor has the great advantage of having no commutator, with its attendant troubles disadvantages compared with D.C. motors. These are difficulties of speed control and inflexibility.

The definite relationship between the torque and speed of an induction motor renders it unsuitable for certain classes of work. For this reason A.C. commutator motors (*see* Fig. 26) have a considerable field of usefulness, especially on single-phase supply, and where high torque over a wide range of speeds is desired, for example, in

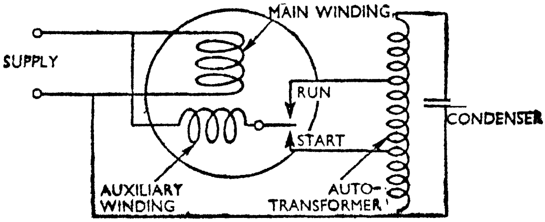


Fig. 25. There are several possible arrangements of the capacitor motor. This circuit arrangement shows the condenser connected across a step-up auto-transformer, which causes the current in the auxiliary winding to lead that in the main winding by a considerable angle, giving a two-phase effect. The change-over of the switch from "start" to "run" is actuated automatically by a centrifugal device on the shaft.

traction work and electric cranes.

There are many types of A.C. commutator motor, both single-phase and three-phase. They can be given series or shunt characteristics similar to those of D.C. motors.

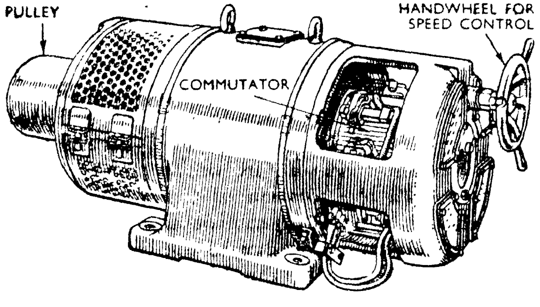


Fig. 26. Three-phase variable-speed commutator motor of the type with one fixed and one movable group of brushes. Speed is controlled by means of the handwheel. Motor is started with the brushes set for minimum speed and switched directly on to the supply.

If the connections to a D.C. series motor are reversed, the motor runs in the same direction, since both the field and the armature current are reversed simultaneously. So, theoretically, if such a motor is supplied with A.C. it should run satisfactorily. The fact that the current is alternating, however, calls for some modification in the design.

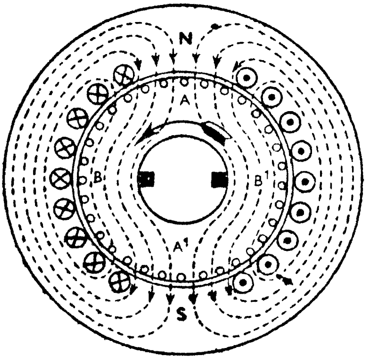


Fig. 27. A.C. series commutator motor—diagram representing the field system and armature. The conductors A and A^1 opposite pole centres have the greatest *generated* e.m.f., due to rotation in the field, whereas the coil formed by the conductors B and B^1 has the greatest *induced* e.m.f., arising from transformer action between field and armature windings. The induced voltages are, therefore, short-circuited by the brushes, which are placed where there is no generated voltage, that is, at the neutral points as in a D.C. machine. It should be noted that **generated e.m.f. is produced by relative motion between conductor and field, whereas induced e.m.f. is produced by variation of the magnetic flux linked with a circuit or coil, as in a transformer. This fact sometimes escapes notice.**

Laminated Systems

In the first place, the whole magnetic circuit must be laminated, the field magnet system as well as the armature core. For this reason salient or projecting pole construction is unusual; the field-magnet system is smooth-cored like the stator of an induction motor, with the field winding in slots.

Secondly, there are induced e.m.f.'s in both field and armature windings due to the alternation of the field, and these also call for modification in design.

The induced e.m.f. in the field winding lags 90 deg. behind the current and its only effect is to lower the working power factor of the machine, since the field winding acts like a reactor in series. The effect is countered by having as few turns as possible, the magnetic circuit being designed on generous lines to have a low magnetic reluctance. This calls for a small air-gap.

In the armature there are no less than three distinct e.m.f.'s: (*a*) the normal *generated* or back-e.m.f. due to the rotation of the armature in the field; (*b*) an *induced* e.m.f. of self-induction due to the alternating current in the highly inductive armature itself; and (*c*) an induced e.m.f. in the armature winding due to transformer action between field and armature windings. Let us consider these three e.m.f.'s separately.

Varying e.m.f.'s

(*a*) The generated e.m.f. is greatest in those conductors opposite the pole centres (Fig. 27) and the brushes are placed at the *neutral points* on the commutator; that is, where no voltage occurs between adjacent segments when the machine is running from a D.C. supply (as it will).

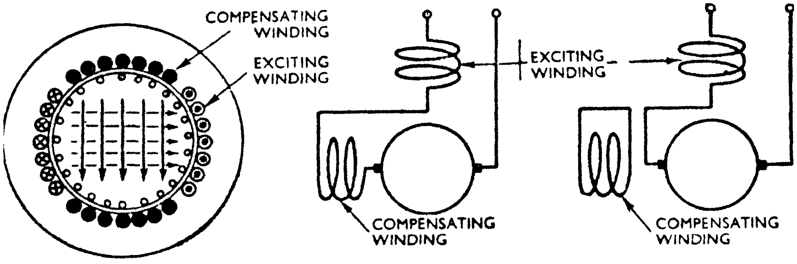
(*b*) The current in the armature produces its own field *at right angles to the main field*. This is an alternating flux and sets up self-induced e.m.f.'s (for the armature is highly inductive) opposing the flow of current through the armature. So, in order that the necessary current shall flow freely, it is necessary to neutralize the "cross" field by means of a compensating winding on the stator.

Compensating Winding

This winding is arranged at right angles to the main field winding and has the same number of ampere-turns as the armature has from brush to brush. The two groups of ampere-turns are opposed to each other so that their nett magnetic effect is nil. In this way the cross field is entirely eliminated.

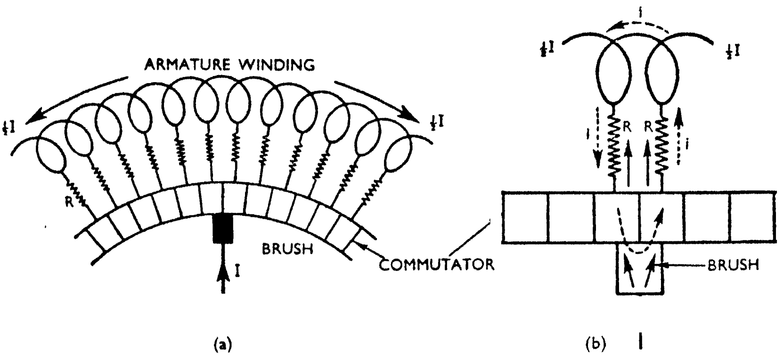
The arrangement is illustrated in Fig. 28 (left). The compensating winding may be connected either in series with the main circuit as in Fig. 28 (centre), or it may be short-circuited on itself as shown in Fig. 28 (right).

In this latter case, the alternating current in the armature induces, by transformer action, a current in the compensating coil, its value being such as nearly to balance the magnetic effect of the armature



COMPENSATED SERIES MOTOR

Fig. 28. (Left) The full-line arrows indicate the general direction of the main field produced by the exciting winding. The broken-line arrows give the direction of the flux produced by the currents in the armature windings. The compensating winding is arranged to neutralize this armature flux and so to render the combination of armature and compensating winding virtually non-inductive. (Centre) Series connection of the compensating winding. (Right) Short-circuited compensating winding in which the current is produced by transformer action.



(a) (b)

USE OF HIGH-RESISTANCE MATERIALS

Fig. 29. Use of "preventive resistances" *RR*, to limit circulating currents due to e.m.f.'s induced by transformer action in the armature winding. (b) is an enlarged part of (a) showing the paths taken by the main current *I* and induced circulating current *i*. Effective resistance in the main circuit is ½*R* and in local circuit 2*R*. A ring-type armature winding is shown for simplicity. It must be remembered that the currents are alternating and that arrows indicate the positive directions.

current. The condition is the same as for a transformer on short-circuit test in which the magnetic flux is reduced almost to zero.

Induced e.m.f.

(*c*) The e.m.f.'s induced in the armature coils by transformer action between the main field winding and the armature winding are greatest in the conductors *midway between the pole centres*, since the armature coil with the greatest e.m.f. is the one whose magnetic axis is parallel to the main field.

Consequently, at the commutator the voltages produced by transformer action are greatest between segments just where the brushes are situated, at the so-called neutral points. The result would be serious sparking if means were not provided for limiting the current passing between segments short-circuited by a brush.

This is done by making the connections between the armature winding and the commutator segments of high-resistance material, as illustrated in Fig. 29. If the brushes are narrow enough not to touch more than two segments, there will be two "preventive resistors" in *series* in each short-circuit path, whereas in the main circuit there will be two such connectors in *parallel* at each brush.

The resulting losses in the main circuit are more than compensated by the reduction of the losses arising from the induced circulating currents.

Difficulties of commutation due to the effects discussed rise rapidly with increase of frequency. Except for small motors the frequency should not exceed 25 c.p.s.; electric railways operating from a single-phase supply sometimes have their power generated at frequencies as low as 15 c.p.s.

Three-phase Type

The principle of the three-phase series commutator motor is in general the same as for the single-phase type. However, the difference in the nature of the supply calls for some modifications.

The general arrangement is indicated in Fig. 30 (left). There are three brush sets per pair of poles spaced 120 electrical deg. apart, and the speed is controlled by moving all brushes simultaneously round the commutator by means of a hand-wheel. There is a tendency for instability at the lowest speeds but, by using one set of fixed brushes and one movable, this disadvantage can be avoided and at the same time a high power factor can be secured.

One fixed brush and one movable brush are connected to the opposite ends of each secondary winding of a three-phase transformer with the primary windings star-connected in series with the stator windings, as illustrated in Fig. 30 (right).

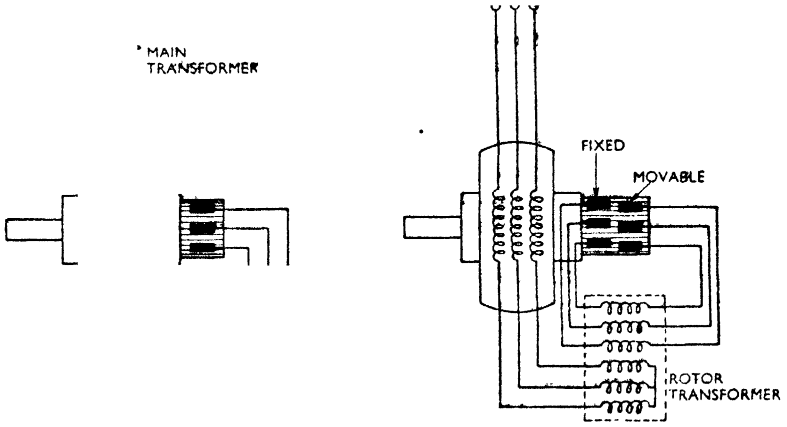
The three-phase shunt motor is a motor which runs at more or less constant speed at all loads, and the speed can be adjusted to any desired value by changing the tapping points on a transformer between the supply mains and the brushes, which are fixed in position. The circuit is shown in Fig. 31.

There are many other forms of A.C. commutator motors, of which space does not allow description here, but most of them involve the main principles which have been considered in this chapter.

Factors Determining Choice

The class of work to which a motor is most suited depends primarily on the relationship between speed and torque, that is, on the manner in which the speed changes as the load is varied.

Plain induction motors of both the slip-ring and squirrel-cage



THREE-PHASE SERIES MOTOR

Fig. 30. (Left) Simple form with movable brushes. Transformer is necessary because voltage at the commutator must be low. Alternatively, transformer can be situated between stator windings and brushes at X, enabling a high-voltage stator winding to be used. Speed is controlled by moving the brushes simultaneously round the commutator through equal angles. (Right) Modified series motor with fixed and movable brushes. The advantages are the attainment of high power factor and also stability at the lowest sp types have a fairly level speed characteristic, the speed falling by usually less than 5 per cent between no load and full load. The squirrel-cage type is slightly better in this respect. So, for all purposes, where one fairly constant speed is needed, the plain induction motor meets the requirements. It is comparatively inexpensive, robust and requires very little maintenance.

The choice between squirrel-cage and slip-ring types is determined by the starting conditions; that is, whether the motor may be started under very light load or no load, or whether it has to start against a heavy load torque. In the former case, the squirrel-cage motor is suitable and would be chosen as the cheaper and more robust.

On the other hand, if the motor has to start under heavy load the squirrel-cage motor with its poor starting torque would be unsuitable; the slip-ring type would be installed, provided with starting resistances in the rotor circuits as already explained.

Special Squirrel-cage Motor

A squirrel-cage motor with high starting torque has been evolved and is in extensive use. The rotor is provided with *two* independent squirrel cages, one of normal design giving maximum torque at about 15 per cent slip, and the other having comparatively high resistance and low inductance so proportioned that its maximum torque occurs at standstill.

As the motor accelerates, the torque of the high-resistance cage decreases, whilst that of the normal low-resistance cage rises. The two together give a high total torque over the whole range of speeds between zero and the full-load value. A disadvantage is the large current taken during starting, unless the stator applied voltage is reduced, thereby reducing the starting torque.

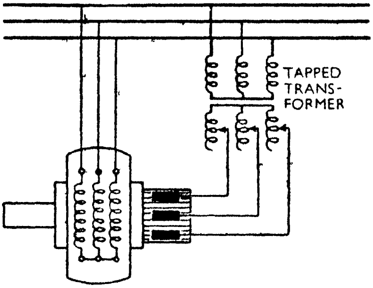


Fig. 31. Three-phase shunt motor. The brushes are fixed and the speed is adjusted by changing the tapping point on the transformer.

Where a number of different fairly constant speeds are required, or where a continuously adjustable speed is needed, as in the driving of paper-making machines, printing presses, cranes, high-speed lifts, and so on, one or other of the various forms of A.C. commutator motor with shunt characteristics would be selected. The final choice would in turn depend on the nature of supply, whether three-phase or single-phase, and on the size of the motor.

Motors with series characteristics, that is, where the torque is highest at low speeds and diminishes rapidly as the speed rises, operate in such a way that the speed falls automatically and to a large extent as the load increases. These are particularly suitable for traction work and for the driving of cranes, fans and some types of pumps. They develop a large starting torque without taking excessively large currents, this being a very desirable feature where frequent starting and stopping under load are required.

CHAPTER 10

TRANSFORMERS

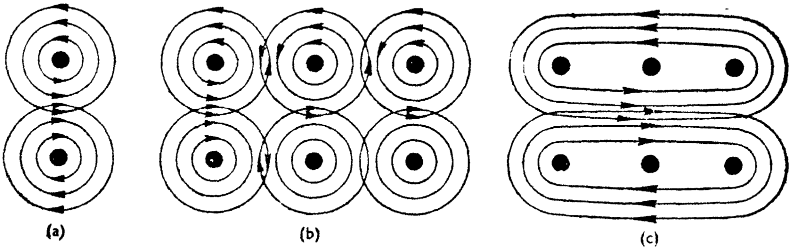
NO-LOAD CONDITIONS. RATIO OF AMPERE TURNS. LOSSES. REDUCING MAGNETIC LEAKAGE. COPPER LOSSES. OVERALL EFFICIENCY. COOLING OF POWER TRANSFORMERS. OIL COOLING. CONSERVATORS. POLYPHASE TRANSFORMERS. INSTRUMENT TRANSFORMERS. MEASURING PROPORTION OF TOTAL CURRENT. RATING OF CURRENT TRANSFORMERS. SIZE OF PRIMARY CONDUCTORS. CONSTRUCTION OF POTENTIAL TRANSFORMERS. AUTO-TRANSFORMERS.

THE transformer is a piece of electrical equipment generally used for changing alternating current from one voltage to another. It may be either of the step-up or step-down type, depending upon whether the voltage is to be raised or lowered. Both types are fundamentally the same, the chief difference, as shown later, lying in the relative sizes of the windings.

By using a step-up transformer, current from an alternator or from A.C. mains can be raised to a higher voltage. For instance, if an alternator generates at 6000 V the pressure can be stepped up through a transformer to 11,000 V or higher.

As explained in Chapter 13, high voltage is used for transmission purposes because, for a given power, the current is thereby reduced. The smaller the current, the smaller the losses in the resistance of the cables. In other words, for a certain permissible loss smaller cables can be employed, thus effecting great economy in materials.

At the consumer's end, however, high voltage is not safe and it is necessary to step the supply down to a lower pressure. For this, a step-down transformer is used. For instance, where a transmission scheme operates at 11,000 V and it is required to deliver the current



PRODUCING A STRONGER MAGNETIC FIELD

Fig. 1. It has been established that when a wire carrying a current is wound into a coil, the magnetic field around this conductor becomes larger and stronger. At (a) the dots represent the section of a single turn of wire at right angles to the paper, and the lines represent the lines of force. (b) When several turns adjoin, the fields "add" up to produce the single field (c), similar to that of a bar magnet.

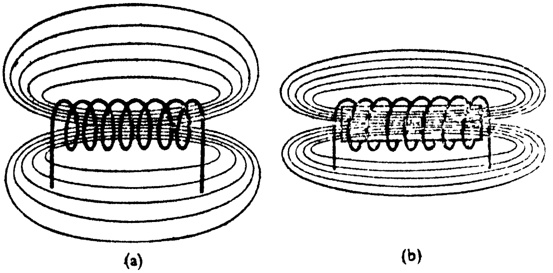


Fig. 2. (a) Diagram illustrating the field round a coil carrying a current. (b) Introducing an iron core will concentrate the lines in a smaller area and increase the strength of the field.

to consumers' homes, the voltage is transformed or stepped down to 230 V.

Transformers used on A.C. are usually of the static type; that is, they have no moving parts.

This is not so with direct current, with which rotary transformers must be used. These usually consist of two machines coupled together, one a generator and the other a motor. The motor operates at the voltage of the supply, while the generator delivers current, either A.C. or D.C., at the required voltage. Details of the system will be clear from the chapters dealing with the generator and the motor, and in the present chapter we deal solely with the static transformer.

Transformer Principle

One of the most important pieces of electrical equipment, the static transformer, is also one of the simplest. In principle it consists of two coils of wire wound over an iron core.

To understand how the transformer works, it is first necessary to be acquainted with the principles of electromagnetic induction and self-induction. Readers who are not clear on these matters should re-read the earlier pages, because here we can pause only to recall briefly the essential facts.

We know that a current is always attended by a magnetic field. A wire carrying a current is the hub of a concentric series of circular lines of force. When the wire is wound into a coil, the circular lines of force overlap (Fig. 1) and add together to produce a stronger field.

The field is made yet stronger, as suggested in Fig. 2, if a core of soft iron is placed in the coil. Magnetic lines of force find it easier to pass through iron than through air. Therefore, when an iron core is introduced the flux tends to concentrate in the iron and the immediate neighbourhood rather than spread out in surrounding space.

If a *closed magnetic circuit* is provided, as in Fig. 3, the iron core being in the shape of a loop, the field concentrates almost entirely within the iron (and the windings), as there is no reason for it to force a way through the reluctance (or resistance) of the air.

In an inductance, as such an arrangement is called, current and e.m.f. behave in an interesting way. As soon as voltage is applied, current starts to flow and lines of force begin to expand outward from each turn of wire and so to pass through or "cut" all the adjacent turns.

Now we saw previously that a conductor "cut" by lines of force has an e.m.f. induced in it. So the building up of current in a coil is

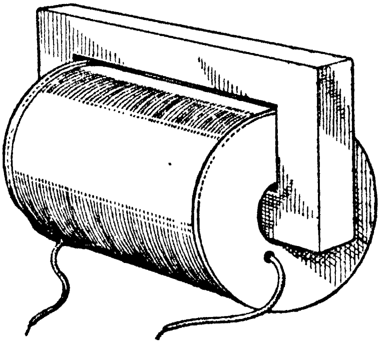


Fig. 3. Coil of wire on a "closed" magnetic core. The field created by the

accompanied by the "self-induction" of an e.m.f. It is not surprising that this is a reverse, or back, e.m.f. which opposes the applied voltage —if it were otherwise, the current would build itself up and we should be getting something for nothing, which is contrary to all the laws of nature.

Actually, the back e.m.f. is the electrical equivalent of inertia. It is present in every electrical circuit to some degree and is what prevents current reaching full strength instantaneously when an e.m.f. is applied. In the case of an iron-cored coil, where the inductance is considerable, the build-up of current may be delayed very appreciably.

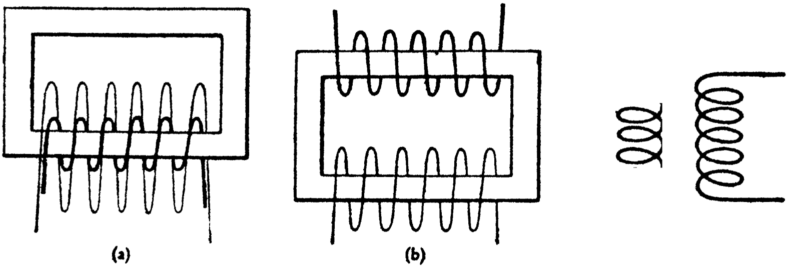
In overcoming this back e.m.f. the external source of applied e.m.f. expends extra energy. This energy is not lost but goes into the magnetic field, and the field is, therefore, a form of energy.

Return of Energy

When the applied e.m.f. is removed, or decreases, the current drops and the circular lines of force collapse inward. Again they cut the turns of the coil—but this time in the opposite direction, and the induced e.m.f. is in the same "sense" as the applied voltage.

In other words, the energy which was put into the field is returned to the circuit in the form of a prolongation of current. If the circuit has been opened and current cannot flow, the pulse of returned energy builds up a high e.m.f. and dissipates itself by sparking across the contacts and in oscillatory currents and electro-magnetic waves which pass out into the ether, or surrounding space.

If a direct e.m.f. is applied to a coil, the current builds up, overcoming the back e.m.f., and finally



(a) (b)

DIAGRAMMATIC REPRESENTATIONS OF A SIMPLE TRANSFORMER

Fig. 4. (a) and (b) show two ways of representing, diagrammatically, how a simple transformer is constructed. Explained simply, we find that it is a coil with another winding placed so close that it is cut by the field set up by the current in the first coil. (c) The theoretical symbol which is employed in circuit diagrams.

reaches the value permitted by the resistance of the wire. Voltage, current and resistance then have the values indicated by Ohm's Law. Once the maximum steady value of current has been reached, the magnetic field, while still present, and, indeed, at its strongest, is steady and there is no further cutting and no back e.m.f.

Changing Current

But suppose that we apply an alternating e.m.f.; for example, connect the inductance to the A.C. mains supply. In this case, the current is always changing, never steady, and there is always an induced e.m.f.

This means that the current never reaches the value which the resistance alone would permit. As the applied e.m.f. rises, the current lags behind. Then, before the current catches up, the e.m.f. begins to fall or to rise in the opposite direction.

The way current and e.m.f. are related, that is, their phase relationship, is important. But we have now brought out those points which are vital to even an elementary understanding of the transformer.

Simple Transformer

A transformer is, in its simplest form, a coil with another winding placed so close that it is cut by the field set up by current in the first coil. Since any conductor cut by lines of force has an e.m.f. induced in it, this second coil receives an induced e.m.f. *as long as the lines of force are in motion* (Figs. 4 and 5).

The first coil, the one to which an e.m.f. is applied, is known as the primary, and the second winding, in which an e.m.f. is induced, is called the secondary. In some transformers there is more than one secondary.

If D.C. is applied to the primary of a transformer there will be a pulse of e.m.f. in the secondary while the magnetic field is building up, and another, in the opposite direction, when the circuit is broken and the field collapses. Such pulses are not very useful and so for practical purposes A.C. is always applied to the primary, so that there is a continually changing field and always an induced e.m.f. in the secondary.

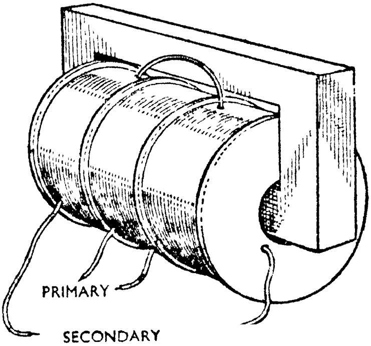


Fig. 5. Illustrating a practical form of construction for a small transformer. Note how the secondary is wound on two bobbins, one each side of the primary, to make sure that it is "cut" by the lines of force created by the primary.

The secondary e.m.f. follows all the variations of the magnetic field which, in turn, follows the variations of the applied A.C.; that is, the secondary e.m.f. is an alternating one, like that in the primary.

When a lamp, or other "load," is connected across the secondary, current flows and energy is dissipated. Obviously this energy comes from the source applied to the primary, but just how do we explain this transference of power between two windings which will be found to have no common electrical connection?

We have already seen that the magnetic field is a form of energy and so we can appreciate dimly that it is the medium by which energy is transferred from the primary to the secondary. This magnetic coupling of the two coils is known as the *mutual inductance.* The next step is to remember that as soon as current begins to flow in the secondary it sets up its own lines of force and these, naturally, cut both the secondary winding and the primary.

Effect of Load

Self-induction in the secondary, as in the primary, tends to oppose any change of current and, therefore, adds to the work of the primary field. In other words, the field set up by the secondary opposes that of the primary and, therefore, tends to weaken it. Consequently, there is less back e.m.f. in the primary and the primary current increases. The larger the secondary current, the lower the reactance of the primary and the higher its current; which, of course, is only what is to be expected.

That gives us a general idea of how the transformer works. Now we can look into such matters as what determines how much current can be drawn from the secondary and what decides its voltage.

The amount of current which may be taken from the secondary depends upon the number of lines of force and the rate at whch they cut the winding. The number of effective lines of force, or useful flux, is dependent largely upon two factors, the number of ampere-turns in the primary and the material of the core.

For instance, if a primary consisted of one turn only, the flux would be determined by the amperes flowing. If two turns were made, the flux would be doubled. Therefore, flux is proportional both to the amperes and to the number of turns. The current in amperes multiplied by the number of turns is called the *exciting force* and expressed in "ampere-turns."

It is not difficult, either, to appreciate that the frequency of magnetic cutting also affects the amount of energy transferred. For a given number of ampere-turns, twice as much energy will be "pumped" in and out of the magnetic field if the frequency is doubled. There will be two waves of e.m.f. or current in the secondary where before there was only one.

This means that a transformer is designed to suit the frequency of the supply on which it is to be used. It does not follow that more power can be passed through a given transformer by applying a higher frequency. Actually, the inductance of the primary increases with frequency and, therefore, less current can be driven. If, on the other hand, a lower frequency, or D.C., is applied, the current will exceed the rated value and overheating and damage may result.

Frequency of Supply

In practice, the frequency of most A.C. is of the order of 50 cycles per second, which is a very suitable value for most power transformers.

Before continuing to explain how the value of the secondary current is ascertained, consider now what happens in the primary circuit when an e.m.f. is applied but no current flows through the secondary, that is, the transformer is on "open circuit."

We have seen how, when A.C. is applied to an inductive circuit, in this case the primary winding, a magnetic flux is created and cuts the turns. In cutting, it induces the back e.m.f. of self-induction.

Open-circuit Current

Now the back e.m.f. is not quite as strong as the applied e.m.f., owing to the reluctance of the iron core to give up all its magnetism. There is always a small current, therefore, when a transformer is connected to the supply and it is commonly known as the *open-circuit current*.

It is sometimes termed the *exciting current*, since it is that required to excite or magnetize the iron core, and is always present irrespective of the load.

As the exciting force is proportional to the ampere-turns, we may, by a simple calculation, ascertain the value of the current induced into the secondary in relation to that flowing in the primary.

Assuming a primary winding consists of twenty turns and a current of 5 A passes through it, the exciting force cutting the primary is 100 ampere-turns.

Also, assuming there is no loss of power during the operation, the whole of this exciting force cuts the secondary winding. If the secondary also consists of twenty turns, the current in it is 100 divided by 20, that is, 5 A.

Therefore, where both the primary and the secondary windings have equal numbers of turns, the current and voltage in each are the same, since the flux cuts the same number of turns in each.

Incidentally, if the current of 5 A in each of these windings flowed in the same direction at the same instant, each would assist the magnetization of the iron core, so building up a stronger field and increased back e.m.f. This, as we have already indicated, would be an impossible state of affairs, and it follows, therefore, that the secondary current flows in the opposite direction to the applied current.

The secondary current tends to demagnetize the core and offset the effect of the primary and, in fact, does so except for the small amount of current in the primary which provides the exciting flux. So, for equal turns, the primary current is the secondary current plus the exciting current.

As the flux in the above example cuts the same number of turns, that is, twenty in each winding, the applied e.m.f. equals the induced e.m.f. To see this more clearly, we recall that in the case of the generator a voltage was produced in each turn of the armature winding and all these little voltages add up to the total pressure at the generator terminals.

Similarly with the transformer. The lines of force cut each turn in the winding and generate in each a small e.m.f. As these turns make up one winding, the e.m.f.'s add up to the voltage at the transformer terminals.

Power Relations

Assuming the resistance of primary and secondary are equal, the reactances must be equal, since the number of turns is the same; therefore, the input power (volts and amperes, or *volt-amps*) must equal the output volt-amps.

The power is stated as the product of voltage and current (volt-amps) and not as watts, because a transformer is inductive. Voltage and current are out of phase and their arithmetical product represents the apparent and not the true power.

When speaking of the rating of a transformer, it is the apparent power in kilo-volt-amperes (kVA) which is generally stated.

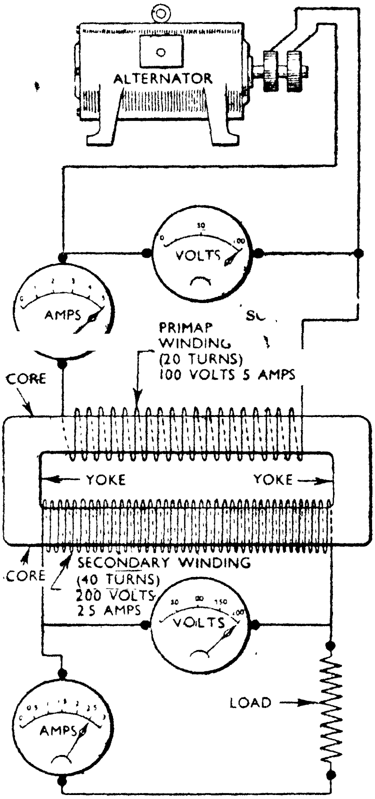


Fig. 6. Showing diagrammatically how the ratio of voltage and current in the two windings of a step-up transformer are dependent upon the ratio of turns in each. The primary winding of 100 V twenty turns carries 5 A, while condary winding of 200 V with forty turns carries 2·5 A.

Few transformers have an equal number of turns in both primary and secondary windings, for their purpose is usually to increase or decrease the voltage. A step-up transformer has more turns in the secondary winding than in the primary, while a step-down has fewer turns in the secondary.

Ratio of Turns

Suppose that the primary of a step-up transformer with a rated capacity of 500 VA has 20 turns, while the secondary has 40 turns (Fig. 6).

As the secondary winding has double the number of turns, the changing magnetic flux cuts twice as many turns in the secondary as in the primary. This will give an induced e.m.f. in the secondary i.e. double that applied to the primary.

Suppose the exciting force in the primary at normal loading is 100 ampere-turns and the applied pressure is 100 V. As the number of ampere-turns in the secondary equals those of the primary, the secondary current at full load is as follows :—

Number of ampere-turns in secondary = 100
Number of turns in secondary = 40
Therefore, current in secondary = 2·5 A

Resultant Voltage

The output voltage of the transformer will be :—

$$\frac{VA}{A} = \frac{500}{2 \cdot 5} = 200 \text{ V, as stated above.}$$

All this shows that once we know the turns ratio of a transformer of a given volt-ampere rating, we also know the voltage output and the two currents. A further example will help make this clear.

A transformer is rated at 6000 volt-amps (or 6 kVA). The input voltage is 12,000 and the output voltage is 400. Since the voltage ratio is also the turns ratio, the primary will have thirty times more turns than the secondary.

As the power output is the product of the voltage and the current, and the input equals the output (disregarding losses), the primary and secondary currents are:—

Current in the primary on full

$$\text{load} = \frac{\text{Volt-amps}}{\text{Input voltage}}$$

$$= \frac{6000\ \text{VA}}{12{,}000\ \text{V}} = 0{\cdot}5\ \text{A.}$$

Current in the secondary =

$$\frac{\text{Volt-amps}}{\text{Output voltage}} = \frac{6000}{400} = 15\ \text{A.}$$

The ratio of the currents is, therefore, 30 : 1, the same as with the voltages. But there is this important difference, whereas the voltage is stepped down, the current is stepped up.

This may be simply expressed as follows :—

$$\frac{\text{Primary turns}}{\text{Secondary amps}} = \frac{\text{Secondary turns}}{\text{Primary amps}}$$

or, alternatively,

Primary turns × Primary current = Secondary turns × Secondary current.

Secondary Load

In these calculations, for simplicity, it has been supposed that current of a specific value is passed through the primary, the secondary current being determined by the ratio of the windings.

We must now view the matter from a more practical angle. We must appreciate that, as was suggested in our first general outline, it is the secondary load which determines both secondary and primary currents.

When there is no load on the secondary, practically no current flows in the primary. Once a load is placed across the secondary, as shown in Fig. 6, current flows and, obviously, providing the transformer can transmit the power, the value of current is determined by the characteristics of the load and e.m.f. across it. The primary current adjusts itself accordingly.

Flux Leakage

The load given in Fig. 6 takes 2·5 A. The secondary is made up of 40 turns and so flux due to 100 ampere-turns is created. To overcome this "negative" flux and sustain the field, the primary must produce another 100 ampere-turns of exciting force. As the primary consists of 20 turns, the current called for will be 100 divided by 20, that is, 5 A.

Further to illustrate how the primary current adjusts itself to the secondary load, we can assume the latter is reduced to 1·25 A. The flux required to drive this current will now correspond to 1·25 × 40, which is 50 ampere-turns. The current in the 20 turns of the primary will now become 2·5 A.

In other words, the current in the primary is always determined by the secondary load which can be increased up to the limits of the transformer's power-conveying capacity.

Except for the reference to open-circuit current, we have so far considered the transformer as being ideal, the power output from the secondary being equal to the input to the primary. We find that in practice, current cannot flow without losses occurring in the resistance

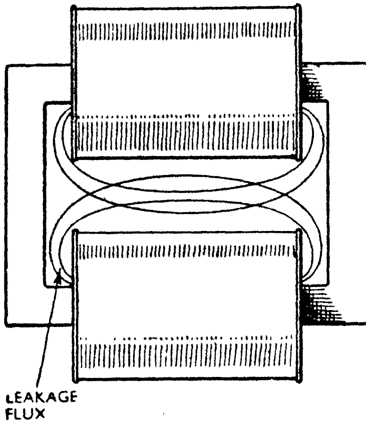


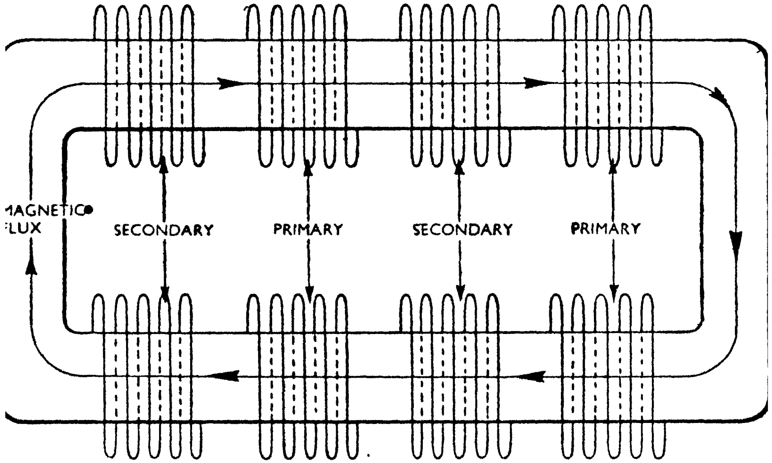
Fig. 7. Schematic diagram representing how air-space between the winding results in a "leakage" of flux, so reducing the efficiency of a transformer.

of the conductors and it is also fairly obvious that losses must arise in the magnetic "circuit."

Up to now it has been assumed that all the magnetic flux produced by the primary ampere-turns is usefully employed in cutting the secondary winding and contributing to the generation of e.m.f. Although modern well-designed transformers are remarkably efficient, some small percentage of the magnetic flux fails to do useful work.

Some of the flux cuts the primary but does not travel as far as the secondary; other lines of force may travel out beyond the secondary; and yet others will be partly "wasted" in the spaces between the windings. Therefore, not all the flux cuts the secondary, with the result that the output is reduced by the amount of stray or leakage flux, as it is called.

The greater the load on the secondary, the greater the amount of stray flux. The reason is that, as the load increases, so more secondary flux opposes the primary flux, the fields repel each other, much like one magnet repelling another, and the primary lines of force are



SINGLE-PHASE TRANSFORMER HAVING SANDWICH COILS

Fig. 8. Both the primary and the secondary windings are divided into four equal coils, two of which are wound on each core, viz., two primary coils and two secondary coils This arrangement of "sandwich" coils reduces the leakage flux.

increasingly diverted through the air space outside the windings.

As the load increases and the leakage flux also, the useful flux cutting the secondary is reduced and the result is that the greater the load, the lower the secondary e.m.f.

Voltage Regulation

The variation of voltage in the secondary between no load and full load is called the *voltage regulation* of the transformer.

Voltage regulation is usually expressed as a percentage, and is approximately 4 per cent in the average transformer.

For example, if a transformer has a primary voltage of 11,000 and a rated secondary voltage of 400, the output voltage at full load will be reduced by 4 per cent to 384 V.

Magnetic leakage is reduced by keeping the space between the primary and secondary windings as small as possible. Transformers designed with a space between the coils, as shown in Fig. 7, would have a high percentage of magnetic leakage. Fig. 8 is a theoretical diagram showing an alternative arrangement where the primary and secondary are split into sections and arranged in the form of sandwich coils.

As each sandwich coil or portion of the secondary winding is wound on the same core as its corresponding portion of the primary, it follows that most of the magnetic flux set up by the primary must cut the secondary.

Another method is to wind the primary over the secondary on both cores, forming what is known as a concentric winding, which is illustrated in Fig. 9.

The winding to which the highest voltage is applied, which is known as the high-tension winding, is always on the outside, with the low voltage, or L.T. winding, next to the core. This construction reduces the chance of a breakdown of insulation, as the highest voltages are removed as far as possible from the iron core, which is usually at earth potential.

The H.T. winding in a step-down transformer is the primary, but in a step-up transformer it is, of course, the secondary. The windings are generally termed H.T. or L.T. windings rather than primary and secondary. After all, in theory either winding can be the

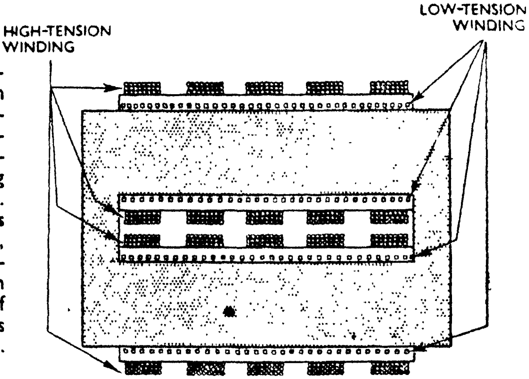


Fig. 9 (right). Single-phase transformer with concentric windings. Illustration shows each winding split into equal portions, one half being wound on each core. L.T. winding comprises one layer on each core, whilst H.T. winding consists of sections each having three layers of coils. The L.T. winding is wound next to the core.

primary if required. By identifying one winding as L.T. we convey the information that it is the one next to the core.

In addition to these leakage losses, transformers suffer further losses which reduce the overall efficiency. For instance, a transformer of rated capacity 100 kVA may have an overall efficiency of 98 per cent. Therefore, 100 kVA of electrical energy is put into the primary but only 98 kVA can be taken from the secondary. The lost 2 kVA of energy is largely dissipated in the form of heat.

Heat Losses

Heat losses are, in fact, the most important the designer must allow for, since they seriously affect the design as regards provision for cooling, as well as the subsequent efficiency of operation. They consist of (1) copper losses, and (2) iron losses.

Wherever current flows in a conductor, heat is generated. Previously it was seen that this heating effect is dependent upon the resistance of the circuit and the strength of the current. In a transformer the heat developed in the resistance of the copper windings is so much wasted energy and is called the "copper loss."

The amount of heat generated is calculated from the formula I^2R, which is the product of the square of the current and the resistance of the circuit. It is sometimes known as the I^2R loss and is expressed in watts.

For example, assuming the total resistance of the winding is 10 ohms and the current is 4 A, the I^2R loss is $4 \times 4 \times 10 = 160$ W.

Iron losses are of two kinds. First, energy is wasted by the production of eddy currents in the iron core, iron being a conductor. The core is cut by the fluctuating field and so current is induced in it. The current is opposed by the resistance and energy is dissipated in the form of heat.

If the iron core was one solid piece, the current induced and the heat generated would be very great. To prevent this the core is made up of a number of plates about ½ mm. thick and insulated from each other either by insulating varnish or by layers of paper.

In these laminated cores, the eddy currents are confined to each individual plate and are not able to circulate and build up into large currents.

Eddy currents are further reduced by using an iron alloy, such as Stalloy, which is an excellent conductor of magnetism but a bad conductor of electricity.

Hysteresis

Now, the second kind of iron loss is brought about by the actual effect of the magnetism itself in the iron core. Magnetizing a material alters the position of groups or "domains" of molecules. Since, in a transformer core, the magnetism is continuously changing due to the applied alternating current, the domains are twisted first in one direction and then round in the opposite direction. This twisting naturally causes a kind of internal friction with resulting loss of energy in the form of heat. This is called the *hysteresis loss*.

As these two forms of iron loss occur whether energy is taken from the secondary or not, they are known as *open-circuit losses*.

The overall efficiency of a transformer is dependent, therefore, upon the value of the copper and iron losses and the amount of magnetic leakage. In practice, the iron losses are the more serious because they are incurred whether energy is being taken from the transformer or not.

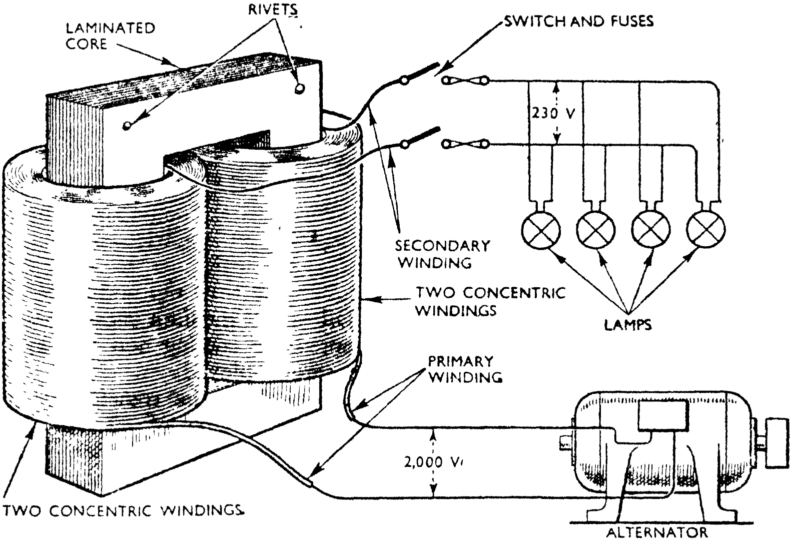
Normally transformers are connected to the circuit at all times and so iron losses waste power throughout the twenty-four hours. On the other hand, copper losses occur only when current is flowing.

Low Copper Losses

Further, as they are proportional to the square of the current, the copper losses, when the transformer is working at quarter load, are only, say, a sixteenth of full-load losses and only one-quarter when working at half load. On open circuit, the primary current which produces the exciting flux is so small that copper losses are negligible and need little consideration.

As the iron losses are the more important, designers usually try to reduce them even if some increase of copper loss is entailed. The ratio of the two in a well-designed transformer is usually 1 : 3. Thus the iron losses are a third of the copper losses.

So far we have said little about the size of the iron core, but it is clearly a point of fundamental importance since it has to "conduct" the field and it is the field which conveys the energy from one winding to the other. As the special core material readily magnetizes, only a comparatively small amount of power is required to excite it and the losses are low. On the other hand, the greater the flux, the



CONSTRUCTION OF A CORE-TYPE TRANSFORMER

Fig. 10. Two windings, primary and secondary, are divided into two equal parts and wound in concentric form on each core. The core consists of a number of thin sheets of Stalloy, or other special magnetic iron alloy, which are insulated with paper on one side and the whole riveted together.

greater is the current producing the lines of force in the core.

As the flux increases, the core tends to become magnetically saturated and a given increase of exciting current produces fewer and fewer lines of force. This increased current produces more waste heat.

A transformer core is made large enough in cross-sectional area to carry easily the flux required. If more than the rated voltage is applied to the primary, the exciting current rises very considerably and causes overheating.

Highly Efficient

Owing to the attention paid to all these points by designers, the overall efficiency of a large transformer is approximately 99 per cent and that of a small unit is 95-96 per cent.

Now we can have a look at constructional details of these power transformers.

There are two main types of design used in the manufacture of power transformers; these being (1) the core type and (2) the shell type. The chief difference between them is that, in the core type (Fig. 10) the windings are wound over the cores, while in the shell type (Fig. 11) the cores are placed round the windings to form a shell.

Cooling Methods

Since the core surrounds a large portion of the windings in the shell type, the windings tend to overheat unless special methods of cooling are applied.

Cooling of both types may be effected by air or oil. Air cooling is rarely adopted in modern transformers above 2 kVA sizes. Where it is employed for larger sizes, there is usually an electric fan which forces the cold air to circulate through the windings and cores.

Oil is the medium most widely adopted for cooling and two systems are employed.

In the first, the transformer is placed in a tank of oil. As the transformer heats up, the temperature of the oil rises. The surrounding air cools the oil at the sides of the tank, circulation of the liquid is set up and cooling is achieved.

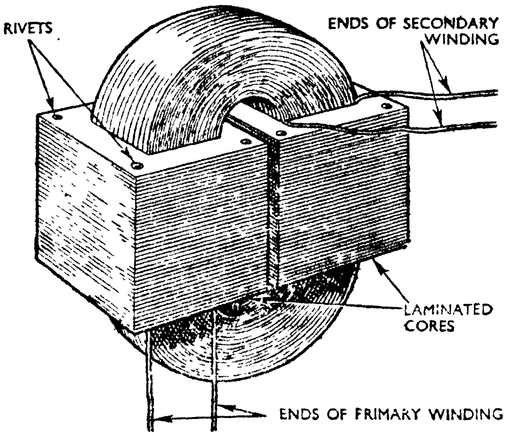
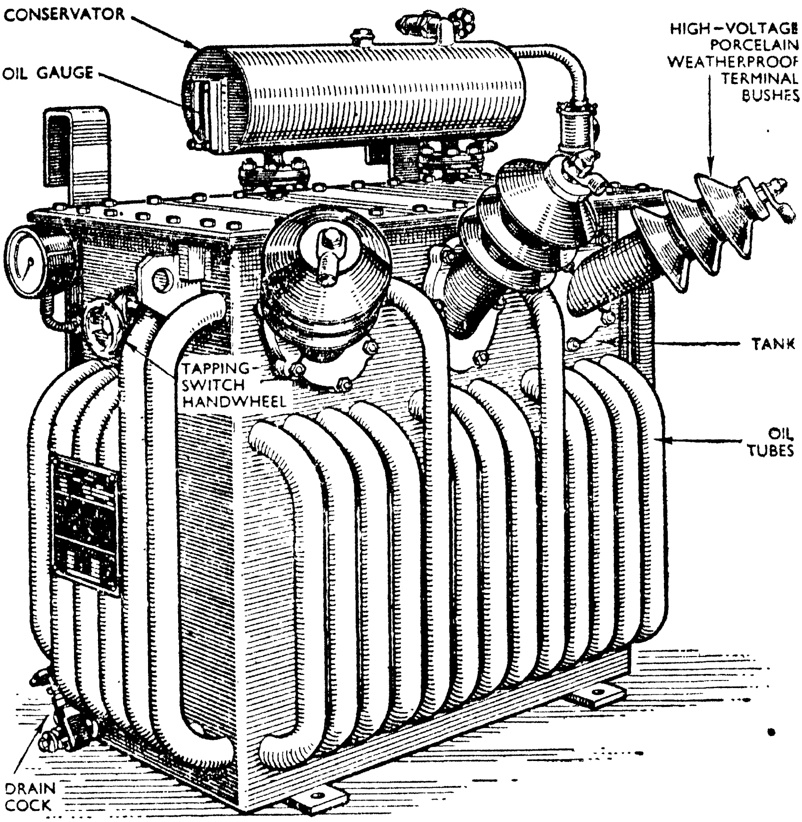


Fig. 11 (left). In the shell-type construction transformer, the core is split into two parts, but as the windings pass through the centre of each part, a magnetic interlinkage is obtained, and this serves as though the windings were mechanically joined together by yokes, which is similar to the core-type of transformer. Both the primary and the secondary windings are wound in concentric form. The cores are made of laminated sheets, and are placed round the windings, forming the shape of a shell, hence the term "shell-type."



50-kVA 11,000/400-V OIL-COOLED TRANSFORMER

Fig. 12. An example of a design suitable for operation in districts where extremes of climatic conditions are frequently experienced. Cooling is by oil-filled tubes

The advantage of this system is simply that a larger area is obtained to radiate the heat; the tank is larger than the transformer and, therefore, its area is greater.

For large transformers this simple design is not adequate and the cooling surface is increased very considerably by providing the tank with tubes exposed to the air. Rapid circulation of the oil is set up and the rate of cooling accelerated.

Fig. 12 shows a transformer where tubes filled with oil are used as an efficient medium for cooling.

Variations in the temperature of the oil owing to changing loads and air temperatures cause it to expand and contract. To allow for this a reservoir must be provided. However, the tank cannot simply be left open at the top, because exposure to air tends to introduce moisture, while the oxygen in the air causes the oil after a while to sludge.

For these reasons, as little of the oil as possible is exposed to the air. This is achieved by fitting a *conservator* or small tank to the main oil tank, connected by a pipe. Thus the oil is allowed to "breathe" and the area of oil exposed to the air is reduced to the size of the conservator.

Action of Breather

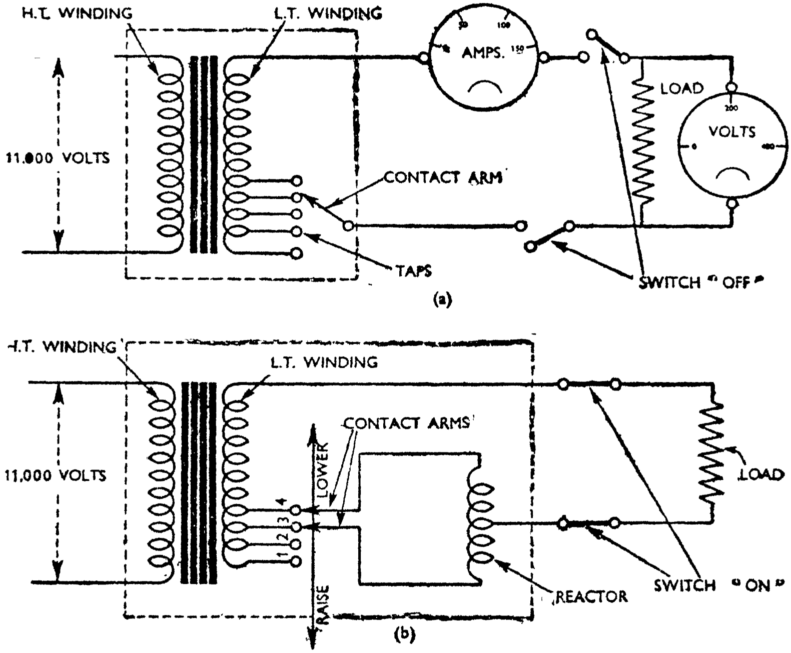
In tropical countries, where there is a high degree of moisture in the air, a device known as a *breather* is fitted to the conservator. A breather is a small container filled with calcium chloride, a substance which readily absorbs moisture.

When the oil in the tank contracts the air drawn in through the breather gives up its moisture to the calcium chloride.

It has been explained that a power transformer has a certain characteristic known as its regulation. As the load on the transformer increases, the output voltage falls. At times the drop may be serious and special provisions are sometimes made to restore the voltage.

To do this, one end of the secondary winding is "tapped" at intervals along its length. From these tapping points leads are taken out to "tap changing equipment." In this way, turns of the secondary may be added or subtracted as required. When the load is increased more turns are added, thereby increasing the primary-secondary turns-ratio and stepping up the e.m.f. Fig. 13a shows a typical wiring diagram.

In the earlier days, tap changing was a major operation on the part of an attendant. The supply to the



OFF-LOAD AND ON-LOAD TAP-CHANGING GEAR

Fig. 13. Typical wiring diagrams. (a) Load must be first switched off, but in (b) the load is on while the tap-changing operation is being carried out

transformer had to be switched off and the cable lead on the secondary terminals had to be removed and replaced on the required tapping. Later equipment incorporated rotary gear, which consisted of a number of contact taps or studs as shown in the illustration. A contact arm fixed to a spindle is moved over the contact studs. This type of tap-changing gear can only be operated when the load is switched off, otherwise heavy arcing at the contacts would occur as the contact arm moved from stud to stud.

Use of Reactor

To obviate switching off the supply, a modified form of tap-changing gear is now available (Fig. 13b). A reactive coil, or *reactor*, inserted between the two contact arms, "absorbs" the heavy current during the movement from stud to stud. The reactor is simply a coil with an iron core and it takes up the current surge by building up its magnetic field.

As the above tap-changing equipments are manually controlled, an operator must visit the transformer site each time adjustment is needed. Where fluctuations in load are known in advance this method is satisfactory apart from questions of labour and time.

In many cases the load fluctuates a number of times an hour during certain periods of the day and so automatic gear is being used to an increasing extent. Fig. 14 illustrates typical automatic tap-changing gear fixed to a transformer.

Automatic tap-changing equipment is actually a form of governor to provide a constant secondary voltage and corresponds to a speed governor on a steam engine. The design varies between different makes but the fundamental principle is always the same.

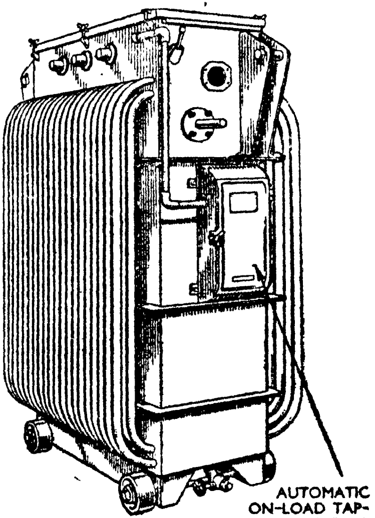


Fig. 14. Transformer fitted with automatic on-load tap-changing gear. This equipment permits of a constant secondary voltage, and is actually a form of governor.

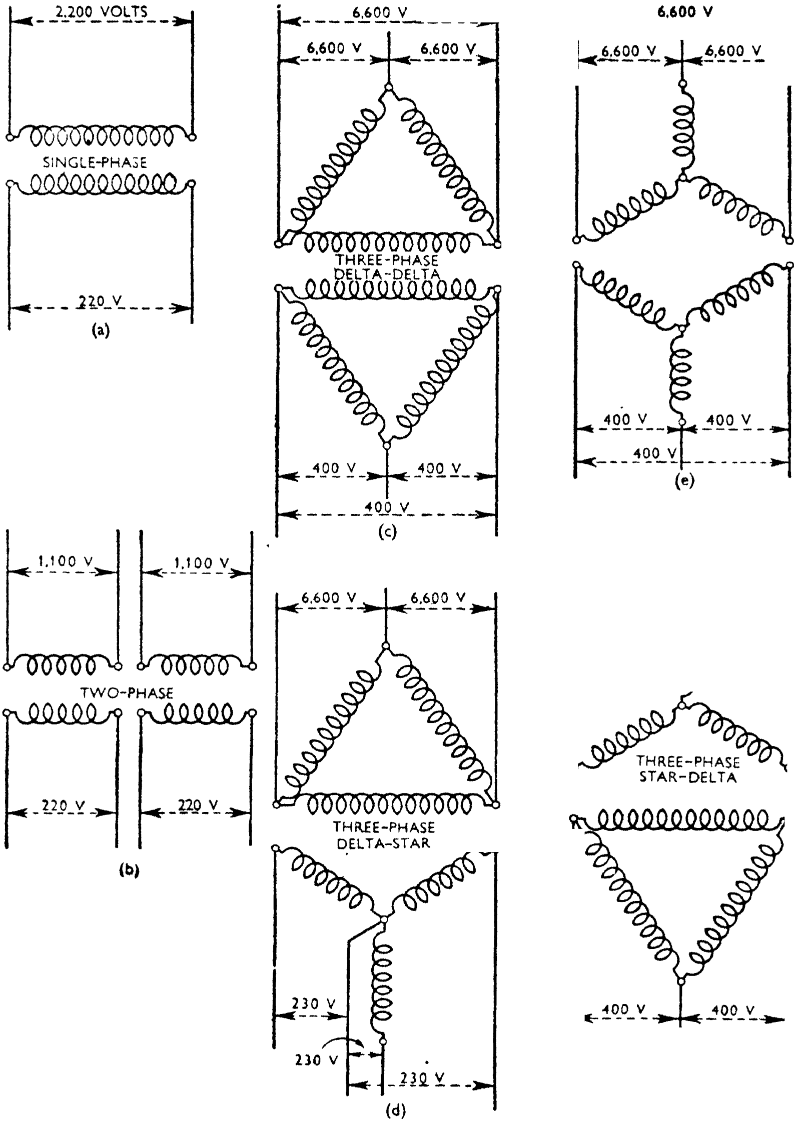
Generally, the equipment comprises a relay and one or more electromagnets which operate the contact arm. When the load is constant, the relay does not function. If the secondary voltage changes, current flows through the trip coil of the relay. The trip coil brings into operation contacts which energize the solenoids.

The solenoids operate the spindle supporting the contact arm, which is thus moved to the next higher or lower stud position.

Slight "Jumping"

The only noticeable effect this automatic equipment has on a supply system is a slight "jumping" of the lights.

So far only single-phase transformers have been considered. For



SOME COMMON POLYPHASE ARRANGEMENTS

Fig. 15. (a) is a single-phase arrangement; (b) two-phase. The other diagrams show three-phase connections; (e) being star-star. The delta connection has the advantage that the line current is 1·73 times the current in each winding. It also improves the balance on the H.V. side if there is an unbalanced load on the L.V. side. With a star connection, the line voltage is 1·73 times the voltage of each winding and there is a neutral point available for connection to a four-wire system as at (d).

supply systems, multi-phase or polyphase transformers are most usually employed.

In practice, polyphase transformers work in two-, three- and six-phase systems. The three-phase transformer is most common because three-phase supply is practically universal in Great Britain and other countries.

Two-phase transformers have two primary windings and two secondary windings wound on soft iron or Stalloy laminated cores as in a single-phase transformer. Fig. 15b clearly shows the four separate windings.

Two-phase transformers are employed chiefly where three-wire or four-wire D.C. systems have been changed over to alternating current. Two-phase systems are, in fact, comparable to the three-wire D.C. electricity system described later.

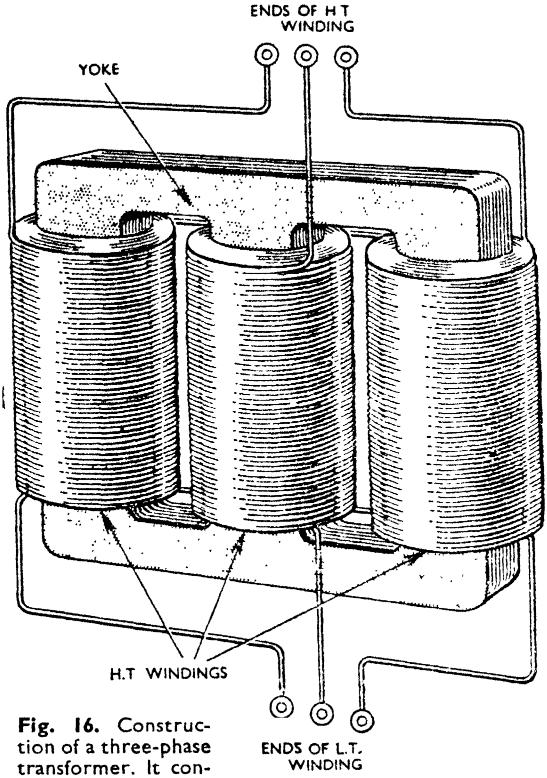


Fig. 16. Construction of a three-phase transformer. It consists of three primary and three secondary windings, wound in concentric form. The secondary windings are wound direct on to the core, but insulated from it. The primary windings are wound over the secondaries, with insulation between the two sets of windings.

Three-phase Transformers

Three-phase transformers comprise three primary and three secondary windings. Fig. 16 shows the simple construction of this transformer, where the coils are wound in concentric form.

The low-tension windings, which are the secondaries in step-down transformers, are wound direct on the core but are, of course, insulated from it.

The high-tension windings, or primaries, are wound over the low-tension windings and adequate insulation is provided between the two sets.

The transformer illustrated in Fig. 17 is a delta-star connected unit. That is, the high-tension or primary windings are connected together in the form of a "delta" or an equilateral triangle (Fig. 15d). The low-tension or secondary windings are connected in the form of a star. That is, ends of each of the three windings are joined together and form the mid-point of the star (Fig. 15d). The three remaining outer ends are taken to the external terminal block.

A lead from the mid-point of the star provides a fourth terminal to which is connected the neutral of a three-phase four-wire distribution scheme (Fig. 18).

The voltage from the mid-point or neutral to any of the other leads, known as the *phase* wires, is lower than that between any two of the phase wires. The voltages are in the ratio of 1 : 1·73.

For instance, if the voltage between two phase terminals is 400, the voltage between any phase terminal and the neutral point is 400 divided by 1·73, which gives 230 V. Conversely, if the voltage of the latter were, say, 240, the voltage between phases would be 240 × 1·73, which is 415 V.

Many Forms of Connection

Not all three-phase transformers are connected in the delta-star manner. In fact, a number of different combinations may be used and Fig. 15 shows a few of the usual connections employed in practice.

There are no important points in which the three-phase transformer differs from the single-phase. The three-phase unit really consists of three single-phase transformers wound on a common core.

Six-phase transformers are used for special purposes, the most usual being to supply six-phase rotary converters. They have three primary windings and usually six secondaries. Fig. 19 gives typical connections of a six-phase star/double-delta transformer.

The three primaries are connected to and receive three-phase current from a three-wire system. The six secondary windings are connected in double-delta form, giving six external leads to go to a six-phase rotary converter. With the development

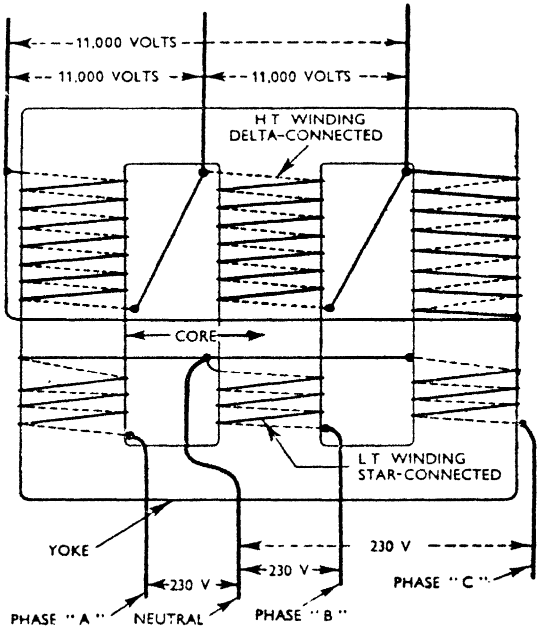
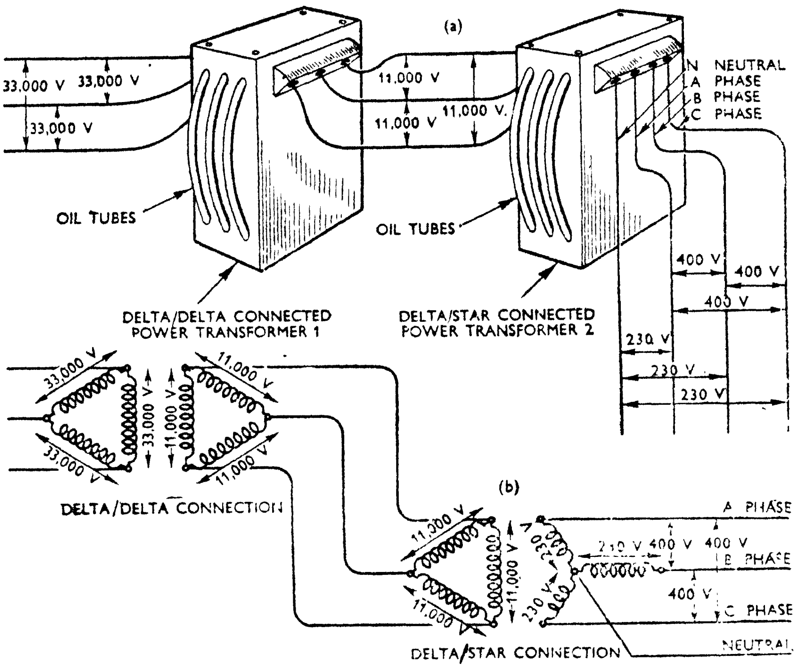


Fig. 17. Principle of the core-type delta/star-connected three-phase step-down transformer, showing all the usual connections of the windings in detail.



THREE-PHASE FOUR-WIRE DISTRIBUTION SCHEME

Fig. 18. (a) High-tension current at 33,000 V is applied to the primary winding of the delta/delta transformer. From this the current is transmitted over the transmission system at 11,000 V to the delta/star transformer. From this secondary winding, current is supplied to the consumers at the standard 400/230 V three-phase four-wire supply. (b) is the theoretical diagram for this three-phase power transformer arrangement, switch and fuse gear being omitted.

of the high-voltage A.C. transmission systems operating up to 132,000 V and, in some cases, even higher, difficulty arises in measuring the voltages and currents. Ordinary types of voltmeter, ammeter and wattmeter cannot be used because of the high insulation and wide clearances which would be necessary. Shunts, dividers and multipliers are used to some extent, but there is a limit to their application.

Instrument Transformers

To overcome the difficulty, special instrument transformers are now in general use for limiting the voltages and currents which pass through the windings of measuring instruments and of control relays.

For example, if a transformer with a step-down ratio of 10 : 1 is employed, the actual measuring instrument will only have to operate at a tenth of the full voltage or current. The meter reading can be multiplied by ten for the true value, or the scale can be directly calibrated if the transformer is a standard part of the instrument.

There are two main types, the current transformer and the potential transformer, and, it may be said, the general principles of these instruments are the same as for power transformers, the main difference being that they are very much smaller, as the power handled is almost negligible.

Current Transformers

A current transformer comprises a laminated core carrying a large number of turns of fine wire for the secondary. The maximum carrying capacity of the wire is rarely more than 5 A.

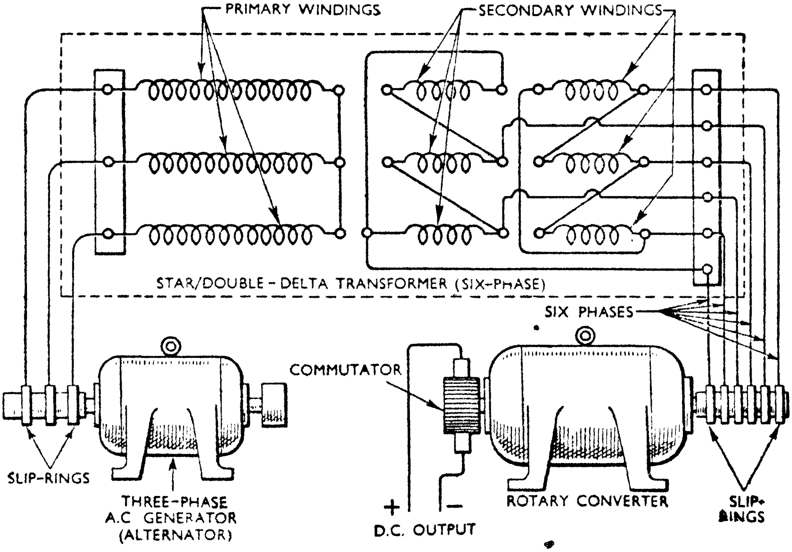
Over the secondary winding are wound two or three turns of heavy gauge copper wire or strip, suitably insulated. The cross-section area of this conductor depends upon the maximum current it has to carry, which is the total current to be measured in the main circuit. Fig. 20 illustrates clearly the main principles of construction.

An ideal transformer, that is, one having an overall efficiency of 100 per cent, would provide in the secondary an exact fraction of the main circuit current, which is the current in the primary winding. In practice, this is not possible and allowance has to be made for this inaccuracy.

In general, a current transformer has a high overall working efficiency when:

(1) A high-grade core material is used (the better the grade of material, the lower the losses).

(2) There are a large number of ampere-turns in the windings. It is obvious that when the primary consists only of one or two turns, high efficiency is not possible. On the other hand, it is not generally



SIX-PHASE STAR/DOUBLE-DELTA TRANSFORMER

Fig. 19. Illustration shows how a three-phase supply is fed from an alternator into the primary winding of a transformer. Six-phase supply is then taken from the secondary connections to supply a rotary converter. D.C. supply is next obtained from the commutator at the D.C. side of the rotary converter.

practicable to have more than three turns owing to the size of the large copper strip relative to the fine secondary winding and the small yoke. Efficiency is, therefore, to some extent sacrificed for compactness.

(3) The load on the secondary is low. Where the current taken by the instrument is small, the secondary can consist of a large number of turns and a high accuracy is achieved.

Where accuracy is essential, it is usual to calibrate the measuring instrument in conjunction with a specific transformer. When using current transformers, it is always essential to ascertain whether they have been calibrated in conjunction with the particular instruments that are to be employed.

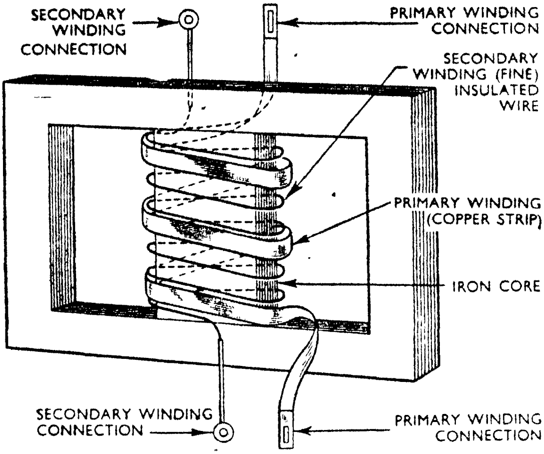

SECONDARY WINDING CONNECTION
PRIMARY WINDING CONNECTION
SECONDARY WINDING (FINE) INSULATED WIRE
PRIMARY WINDING (COPPER STRIP)
IRON CORE
SECONDARY WINDING CONNECTION
PRIMARY WINDING CONNECTION

Fig. 20. Principle of a current transformer, shown above. The primary winding consists of an insulated copper strip which carries the full current in the circuit. The secondary winding comprises a large number of turns of fine insulated wire which carries an induced current of low proportion to the main current. The secondary winding is usually wound direct on to the laminated core, and, as illustrated above, the primary winding is then wound on top of this.

Current transformers are rated in volt-amps in the secondary winding. The usual rating is 5 VA. Transformers of higher ratings are made, usually up to 15 VA, but in these accuracy is sacrificed for output. The latter type is employed chiefly for operating trip coils and circuit breakers.

The ratio of input current to output current varies according to the value of primary current to be measured. The usual full-load output of the secondary is 5 A.

If 20 A were the full-load current of the circuit and the ammeter gave a full-scale reading of 5 A, a transformer with a 20 : 5 ratio would be utilized. Although maximum current through the instrument would be 5 A, the reading on the scale would be 20 A.

Fig. 21 shows an ammeter connected to a current transformer to measure the current in the power circuit.

When calculating the size of conductor to be used in the primary it is usual to take as basis a rate of 1000 A per sq. in. cross-section. This means that when the current in the circuit is 1000 A the cross-section area of the conductor in the primary is 1 sq. in. For other currents the conductor is larger or smaller in proportion.

In mains distribution circuits, the current often considerably exceeds 1000 A, and so it is seen that conductors are of a size which does not lend itself to the winding of coils for small instrument transformers.

To overcome the difficulty, transformers are designed which, in a sense, have no primary winding. The secondary is wound over a ring-shaped core which encircles the cable comprising part of the circuit or distributing feeder. The cable itself then serves as a primary winding having one turn only (Fig. 22).

Voltage Considerations

Up to now, when dealing with current transformers, voltage has not come into the picture. In fact, however, the driving force of the current through the primary winding of a transformer such as we have just described may be a voltage from 230 to 132,000 or more.

This pressure is that present across the system as a whole. The voltage across the primary terminals of the transformer is only the volt drop due to the current overcoming the impedance and may be negligible. The voltage between the winding and the earth, however, will be the phase-to-earth voltage of the system and may be very high.

Since the framework and core of the current transformer are connected to earth, they must be adequately insulated from the conductors. Insulation must be of a high order when the voltage is more than 700. Porcelain is usually employed for the primary and, where the primary is the distributing feeder, porcelain bushes are used.

Fig. 23 shows three transformers with porcelain bushes fitted over the bus-bars or copper connecting wires of a three-phase three-wire system.

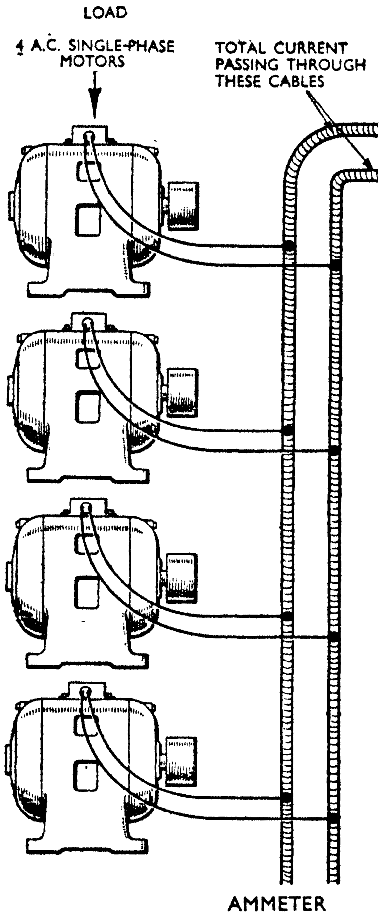
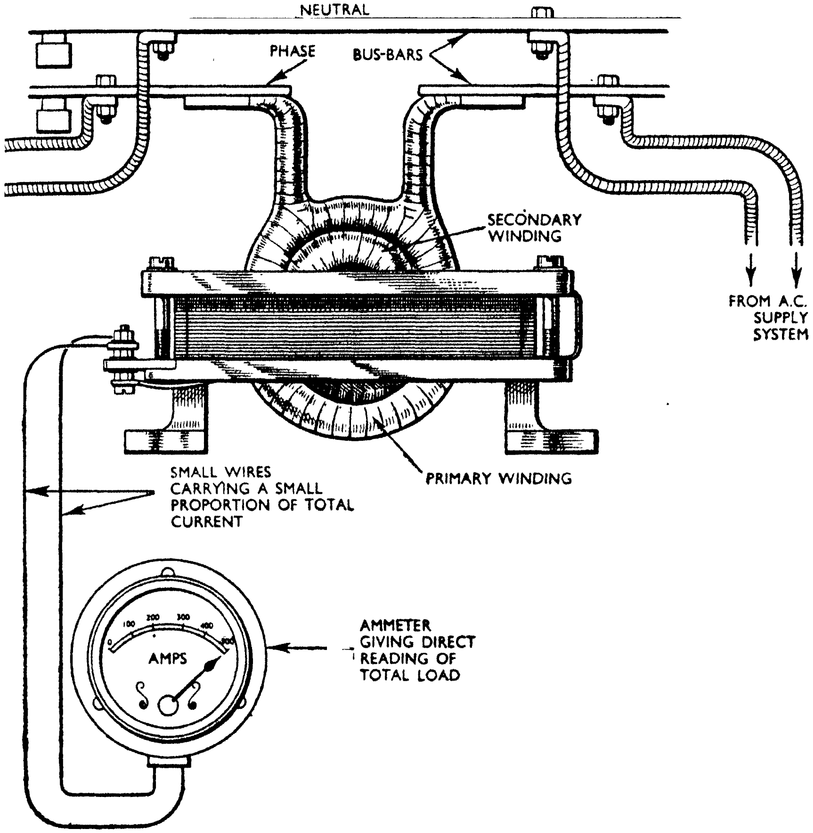

LOAD
4 A.C. SINGLE-PHASE MOTORS
TOTAL CURRENT PASSING THROUGH THESE CABLES
AMMETER

Fig. 21. By connecting an ammeter to a current transformer, this enables us

Fig. 24 shows another type of current transformer which may be used on systems up to 7000 V. Two secondary windings are provided to enable two instruments to be connected to one transformer. In this illustration a watt-hour meter and ammeter are connected. A


NEUTRAL
PHASE
BUS-BARS
SECONDARY WINDING
FROM A.C. SUPPLY SYSTEM
PRIMARY WINDING
SMALL WIRES CARRYING A SMALL PROPORTION OF TOTAL CURRENT
100
200
300
400
500
0
AMPS
AMMETER GIVING DIRECT READING OF TOTAL LOAD

CONNECTED TO A CURRENT TRANSFORMER

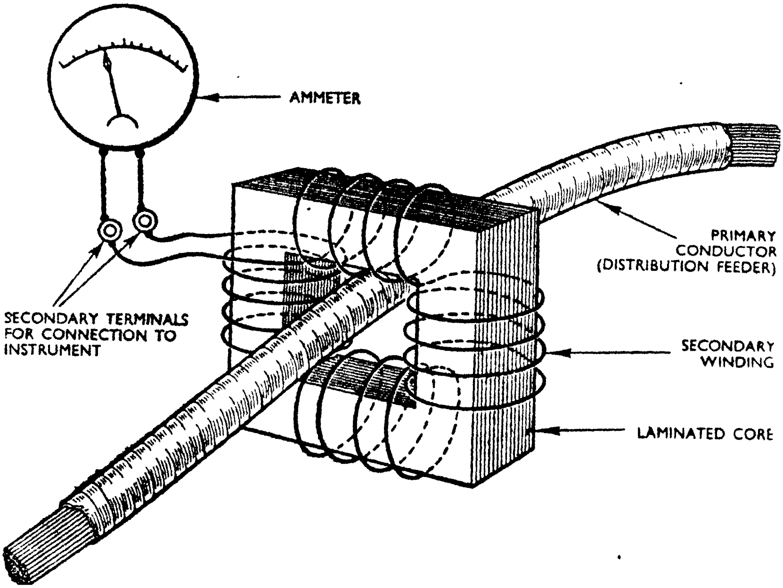
connected in the phase conductor of a single-phase two-wire supply by means of copper-strip bus-bars. Note small proportion of current which actually flows through the instrument. Maximum current in the primary being 500 A, and, in the secondary, 5 A, allowing the instrument to be of reasonable size.

most important feature of this transformer is that, as each secondary has a separate iron core, the circuits are independent and the current through one does not affect the other.

The current transformers so far described have all been air cooled. Where they are connected to high-voltage lines, it is necessary to provide oil cooling. Fig. 25 illustrates a typical transformer having an oil container.

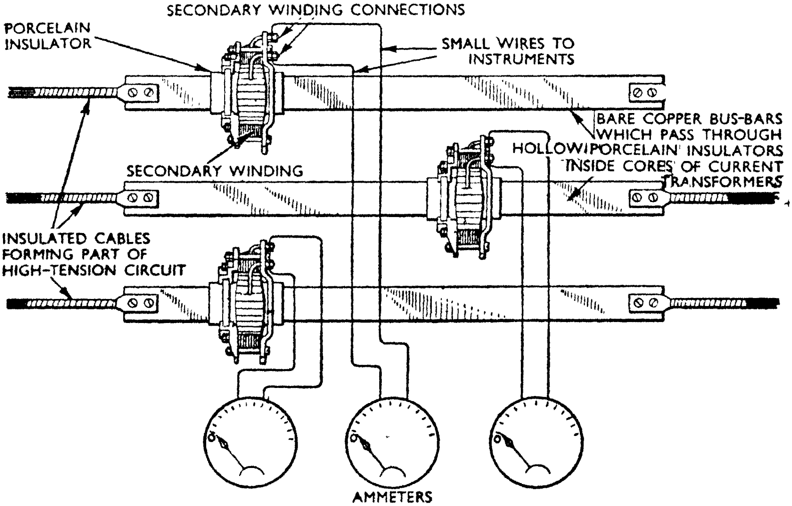
This transformer may be used up to 12,000 V, but the container need not be filled with oil unless the voltage is 7000 and above.

For systems above 12,000 V, special transformers are available. The principle of construction is


AMMETER
PRIMARY CONDUCTOR (DISTRIBUTION FEEDER)
SECONDARY TERMINALS FOR CONNECTION TO INSTRUMENT
SECONDARY WINDING
LAMINATED CORE

CURRENT TRANSFORMER WITHOUT A WOUND PRIMARY

Fig. 22. Frequently current transformers are used which do not have a wound primary. Instead, the conductor or cable comprising the main circuit is passed through a hollow secondary winding, this conductor then operating as the primary.

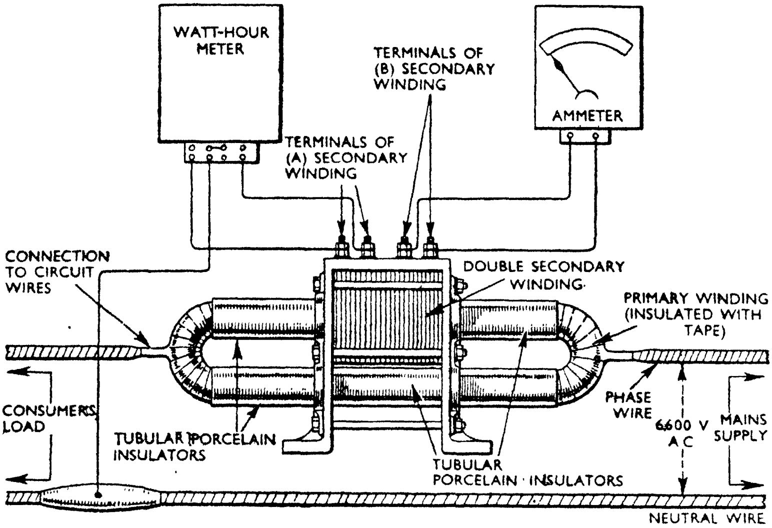

SECONDARY WINDING CONNECTIONS
PORCELAIN INSULATOR
SMALL WIRES TO INSTRUMENTS
BARE COPPER BUS-BARS WHICH PASS THROUGH HOLLOW PORCELAIN INSULATORS INSIDE CORES OF CURRENT TRANSFORMERS
SECONDARY WINDING
INSULATED CABLES FORMING PART OF HIGH-TENSION CIRCUIT
AMMETERS

CURRENT TRANSFORMERS USED ON SYSTEMS UP TO 12,000 V

Fig. 23. Insulated porcelain bushes are provided for these. The system above is an 11,000-V, three-phase, three-wire one where solid copper square bus-bars are used.

similar to the lower voltage types, except that extra precautions are taken against the leakage or flash-over.

Where low voltages are required to operate the coils of specific instruments incorporated in the system, potential transformers are employed. These instruments include wattmeters and also relays.


WATT-HOUR METER
TERMINALS OF (B) SECONDARY WINDING
AMMETER
TERMINALS OF (A) SECONDARY WINDING
CONNECTION TO CIRCUIT WIRES
DOUBLE SECONDARY WINDING
PRIMARY WINDING (INSULATED WITH TAPE)
CONSUMERS LOAD
TUBULAR PORCELAIN INSULATORS
PHASE WIRE
6600 V A C
MAINS SUPPLY
TUBULAR PORCELAIN INSULATORS
NEUTRAL WIRE

CURRENT TRANSFORMER WITH DOUBLE SECONDARY WINDINGS

Fig. 24. Maximum current in the primary winding is 300 A, with a secondary current of 5 A. The maximum voltage of this system is 7000 V. Two secondary windings are provided, each with its own iron core so that each winding is independent of the other. It also shows how a watt-hour meter and an ammeter may be connected to one transformer.

Wattmeters and relays incorporate what are known as voltage coils and current coils. A current coil is supplied either direct from the line or through a current transformer, while the voltage coil is energized either direct from the line when the voltage is low, or through a potential transformer when the voltage is high.

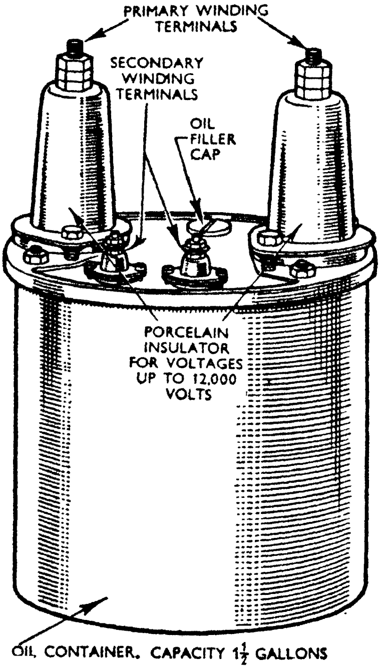
Needless to say, high voltages are not taken direct into instruments because the insulation would necessitate a cumbersome construction which would also be inaccurate.

The principles of a voltage transformer (Fig. 26) are similar to those of the power transformer. Both primary and secondary windings are provided as well as an iron core. They are always step-down transformers, since their purpose is to reduce the voltage to a reasonable working value.

The input voltage may be as high as 33,000, and in this case the pressure exists between the primary terminals because they are connected across the supply system and not in series with it as in the case of a current transformer.

The output voltage of potential transformers has been standardized at 110 irrespective of the high-tension input. This comparatively low voltage has been chosen for reasons of safety and to reduce the necessary insulation of the windings and terminals of the instrument. Further, as the voltage is standardized, the design of the voltage coil portion of the instrument may also be standardized.

In the step-down power transformer, it was seen that the primary or high-tension winding usually had a high voltage of little current, while the secondary gave a heavy current of low voltage.


PRIMARY WINDING TERMINALS
SECONDARY WINDING TERMINALS
OIL FILLER CAP
PORCELAIN INSULATOR FOR VOLTAGES UP TO 12,000 VOLTS
OIL CONTAINER. CAPACITY 1½ GALLONS

are used where the voltage of the system is high, but oil need not be put into the container if the voltage is below 7000 V. It may be noted that the apparatus is more cumbersome than the air-cooled transformer, and owing to its weight being 40 to 50 lb., it cannot be hung on the lines or bus-bars.

The potential transformer, however, differs in that currents in both windings are comparatively small. Only a very small current is required to operate the voltage coil of instruments and therefore it is not necessary to design potential transformers for heavy currents.

Most potential transformers are oil filled, their cables are inserted in oil-filled containers. Dry types may be used below 3000 V.

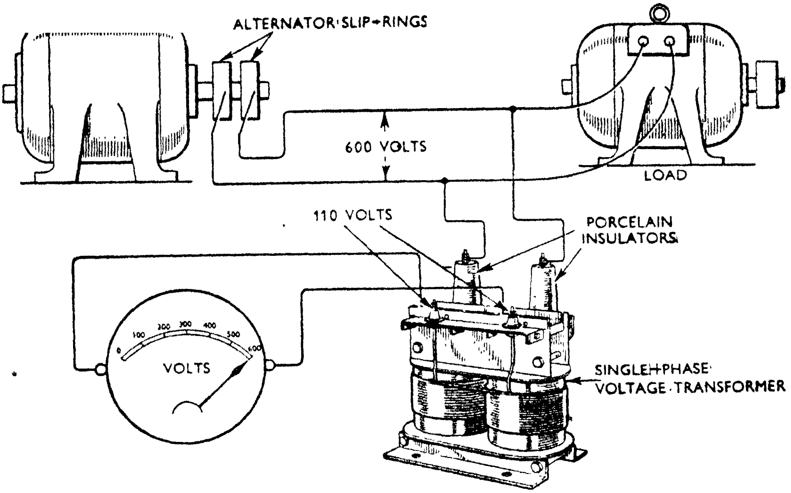
The very high input voltages necessitate a special arrangement of coils. For example, assuming that the high-voltage winding was connected to a supply of 32,000 V, and the winding consisted of two layers of turns, the first layer running from the left to the right and the second layer from the right to the left, the voltage between the first and the last turn would be 32,000. This pressure between adjacent turns would necessitate very high insulation.

Preventing Breakdown

To reduce the insulation and the risk of breakdown, high-tension windings are divided into sections, as shown in Fig. 27b. The voltage between two turns, where there are two layers of turns, cannot exceed an eighth of 32,000, as there are eight such coils. The greater the number of layers per section, the lower the voltage between adjacent turns.

Heavy insulation in the form of oil ducts is provided between coils, between sections, and between layers. To aid insulation the L.T. winding is next to the earthed core and the H.T. is on the outside.

Both windings are protected from overload by fuses. The fuses for the L.T. winding are usually of the



POTENTIAL TRANSFORMER FOR SUPPLYING VOLTMETER

Fig. 26. Although the voltmeter has a low-voltage movement, the reading is that of primary voltage. Similar transformers are used for supplying low voltage to relays.

cartridge type and are mounted either on the top of the chamber or in the terminal box, so that they are easily accessible.

Owing to the very small current in the H.T. winding, little reliance could be placed on the use of ordinary fuse and special types are used. These fuses are spring loaded and the fuse element consists of a short piece of silver wire.

When a fuse operates, the spring is released and prevents the setting up of an arc. The fuses are in the H.T. bushes and are easily removed for replacement.

It has been shown so far that the main object of a transformer is

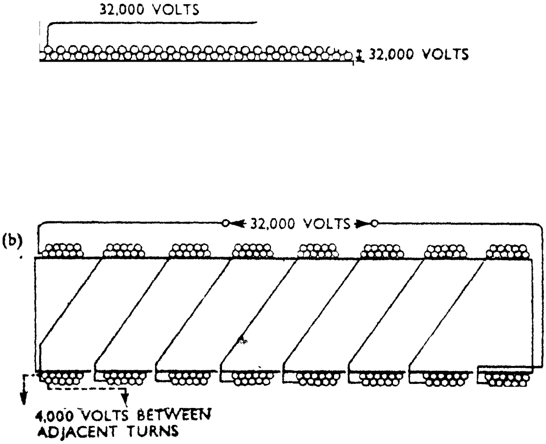


Fig. 27. (a) Showing that total supply voltage exists between adjacent turns. Arrange the coils in sections and the voltage between turns is reduced, depending on number of layers of turns on each coil and number of sections. (b) Illustrating a winding divided into eight sections, each having two layers. By increasing the number of layers and sections, the voltage between adjacent turns is reduced.

either to step-up or step-down the voltage or current or both from a source of supply. A rather special application of the transformer is found in connection with electric motors.

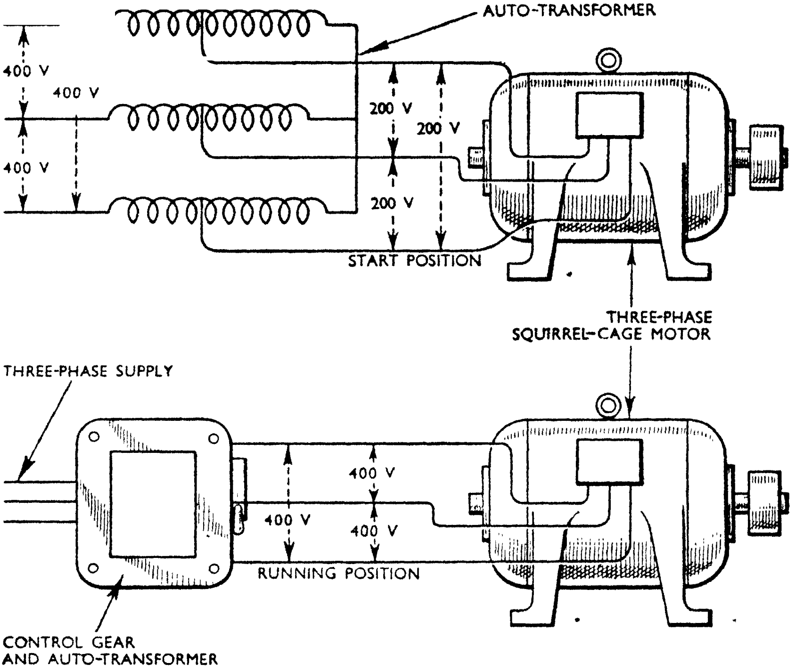
It is usually necessary to limit the current and, therefore, the voltage to the terminals of a motor when it is first started up. There are various ways of achieving this reduction in voltage, one of which is by means of a special transformer known as an *auto-transformer*.

Auto-transformers are used as a current-limiting device for starting squirrel-cage A.C. induction motors. Fig. 28 shows the usual connection made through an auto-transformer to a three-phase motor of this type.

When the supply is first applied to the stationary squirrel cage the current is approximately five times as great as the normal current when the motor is operating at full speed.

Avoiding Overload

It is obvious that this rush of current at switching on would overload the supply cables and, perhaps, damage the motor. By using a step-down auto-transformer whose secondary voltage is of the order of 40 to 60 per cent of the primary voltage, the starting



THREE-PHASE AUTO-TRANSFORMER STARTING

Fig. 28. This auto-transformer is in operation here as the current-limiting device and starter for a three-phase A.C. induction motor. When the motor has reached its normal speed, the auto-transformer is cut out of the circuit by the operation of the starter, and the full voltage of the supply is then applied to the motor.

current can be reduced accordingly. Fig. 29a is a diagram of a step-down auto-transformer where the primary voltage is 400 and that of the secondary 200.

As the secondary voltage is 50 per cent of the primary, the starting current is also reduced by 50 per cent. Therefore, the starting current is 2·5 times instead of 5 times the running current.

An auto-transformer is rather similar to a power transformer except that it has only one winding. This winding is tapped and serves as both the primary and the secondary.

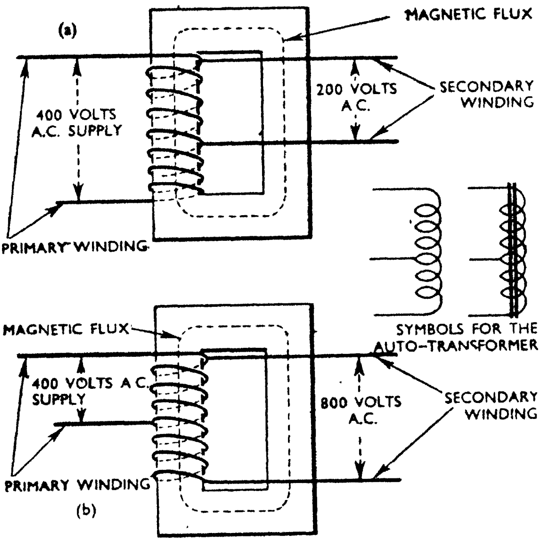


Fig. 29. When a voltage (A.C.) is applied to the primary winding of an auto-transformer, a magnetic flux is set up in the iron core. As this flux will cut all the turns of these windings, an e.m.f. will be induced into the secondary winding, depending upon the number of turns of wire. (a) shows a step-down auto-transformer, and (b) a step-up pattern.

The secondary voltage depends upon the ratio of the turns in the tapped portion to the primary turns (the total number of turns). If, as in Fig. 29a, the tapping is made midway, the secondary voltage is 50 per cent of the primary.

For a step-up auto-transformer the input is connected across a portion of the winding, the whole winding forming the secondary. The voltages again depend upon the ratio of the part to the whole.

It will be appreciated that one part of the winding has to carry both the primary and secondary currents and this adds to the complexities of design. The auto-transformer is also limited in application because the double-wound type has the advantage of splitting up circuits into electrically discontinuous sections. This helps to isolate certain types of fault and is also a valuable contribution to safety.

For example, suppose a transformer is used to operate a bell from 230 V mains. The output voltage may be only 6 V, which is quite safe and, although there are 230 V at the primary, the secondary is isolated from this dangerous pressure by the insulation of the transformer.

If an auto-transformer were fitted in this position, there would be a direct electrical connection between primary and secondary and the whole of the secondary circuit might be raised to 230 V with respect to earth. A person touching either of the secondary leads might receive a serious shock.

CHAPTER 11

ROTARY CONVERTERS AND RECTIFIERS

THREE-PHASE ROTARY CONVERTER. VOLTAGE RATIOS. WAVE FORMS OF ARMATURE CURRENTS. HEATING OF ARMATURE COILS. TRANSFORMER CONNECTIONS. STARTING OF ROTARY CONVERTERS. VOLTAGE REGULATION. MERCURY-ARC RECTIFIERS. EFFICIENCY. THREE-PHASE AND SIX-PHASE RECTIFIERS. ACTION OF THREE-PHASE RECTIFIER. SIX-PHASE CONNECTIONS. IGNITION AND EXCITATION CIRCUITS. SMOOTHING ARRANGEMENTS. INTERPHASE TRANSFORMER. USING METAL RECTIFIERS. RECTIFIER CIRCUITS.

NEARLY all electrical power is generated, transmitted and utilized in the form of alternating current and voltage. This is because, for large-scale generation, transmission and distribution, A.C. plant presents more easily solved engineering and economic problems than do D.C. systems.

There are, however, many purposes for which D.C. is essential, or more generally satisfactory than A.C. The applications for which D.C. is essential include battery charging and all electrolytic processes, such as electroplating and the production of copper, aluminium and other metals by electrolysis. Cinema arc lamps also require D.C.

A.C.-D.C. Comparisons

Purposes for which D.C. is more satisfactory than A.C. include many applications where D.C. motors, with their comparative flexibility of control, give superior performance to A.C. motors. An A.C. induction motor is ideal for continuous running at a more or less constant speed but is inferior to a D.C. motor where frequent starting under high torque, and close speed adjustment, are required.

Suburban electric traction, underground railways, trolley-bus services, and tramways all operate on a D.C. system for these reasons. And there are many industrial purposes for which D.C. motors are to be preferred.

There are numerous cases where an A.C. supply is available but D.C. is required. Fortunately, various methods of conversion from A.C. to D.C. are available. The choice of method depends on the amount of D.C. power needed and, to some extent, on the constancy of voltage required.

Large amounts of D.C. power, as required for electric traction, when derived from an A.C. supply, are obtained either by rotary converters or mercury-arc rectifiers. "Converter" is self-explanatory; a "rectifier" is also a converter but has a special character which will become clear later on.

The rotary converter was first in the field but now has a serious competitor in the mercury-arc rectifier. The former consists of a single machine with both commutator and slip-rings connected to the same armature winding and has the merit of giving a smooth output voltage. The glass-bulb mercury-arc rectifier, which is a very large type of valve, has the advantage of having no moving parts; it requires practically no maintenance and its life is almost indefinite. Some of these rectifiers have a steel tank in place of the glass bulb and the vacuum is maintained by a system of pumps.

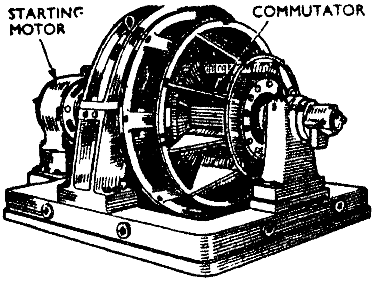


Fig. 1. Rotary converter viewed from the commutator end. The small motor at far end is for starting purposes, and the slip-rings on the A.C. side are mounted on the shaft between the starting motor and the armature.

For small powers, as required for cinema arcs and battery charging, the mercury-arc rectifier is eminently suitable. In this sphere it has a competitor in the metal rectifier, another unit which has no moving parts but which utilizes the one-way conducting property of copper oxide or selenium contacts.

The metal rectifier has an advantage over the mercury-arc where low-voltage supply is needed, say below 50 V. This is because there is a volt drop of 20 to 30 V in the mercury-arc, whereas less than a volt is dropped in the metal rectifier. The latter, therefore, maintains a good efficiency down to low operating voltages.

Metal rectifiers are designed to supply D.C. over a very wide range of values—from one milliamp or so in rectifier-type ammeters and voltmeters, to hundreds of amperes for electroplating. The output voltage can be extended to any desired value by building units with the requisite number of elements in series or tandem.

Now for the principles and operation of these methods of conversion. First, the rotary converter.

Rotary Converters

A rotary converter is not a motor-generator set but a single machine receiving A.C. and giving out D.C. It comprises a stationary field-magnet system with a rotating armature carrying an ordinary D.C. winding connected to a commutator, and, at the other end, two or more slip-rings connected to equidistantly spaced tapping points in the winding. Both the A.C. and the D.C. flow in the same armature winding. The field is excited by a shunt winding between the D.C. brushes or from a separate exciter.

It should be recalled at the outset that the e.m.f.'s and currents in the armature of a D.C. generator are actually alternating, and that it is solely the action of the commutator which gives them a single direction in the external circuit.

A rotating-armature synchronous motor, or an alternator, with mesh-connected or closed armature winding, is essentially the same machine as a D.C. generator except that, instead of a commutator, slip-rings are fitted and connected to suitable points in the winding.

The rotary converter, with both slip-rings and commutator connected to one and the same armature winding, has the same general

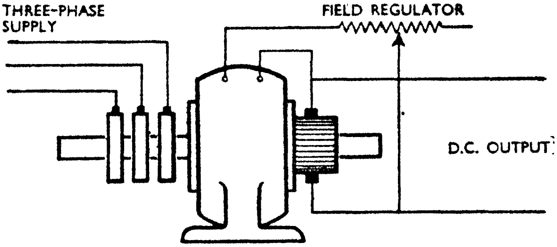


Fig. 2. General scheme and basic circuit of a rotary converter. The armature winding is the same as for a D.C. generator, but slip-rings are provided as well as a commutator. The slip-rings are connected to equidistantly spaced points in the winding. The machine runs from the A.C. side, like a synchronous motor, D.C. being taken from the commutator. The shunt-field winding is supplied from the D.C. output.

appearance and construction as a D.C. generator, and a typical machine is illustrated in Fig. 1. Interpoles or commutating poles are provided as in a D.C. generator, and a damping winding is embedded in the pole faces as in a synchronous motor. When A.C. is suplied to the slip-rings the machine will run as a synchronous motor (after starting and synchronizing as explained in Chapter 8) and, as it performs simultaneously as a generator, D.C. can be taken from the brushes at the commutator. Alternatively, D.C. can be supplied to the commutator and A.C. taken from the slip-rings (inverted rotary converter). The basic circuit for a three-phase (three-ring) rotary converter is indicated in Fig. 2.

The number of slip-rings is equal to the number of phases in the A.C. supplied to the machine, except in the case of the so-called two-phase machine, which has four slip-rings. This is really a four-phase machine, but the term is not much used.

In a 2-pole rotary converter, or a multi-polar one with a wave winding, each slip-ring is connected to one point in the winding. With a lap-wound or parallel-wound armature each slip-ring is connected to as many tapping points as there are *pairs* of poles. The tapping points for any one slip-ring are two pole pitches apart in this case and the slip-rings act as the normal "equalizing rings" in a lap-wound D.C. generator.

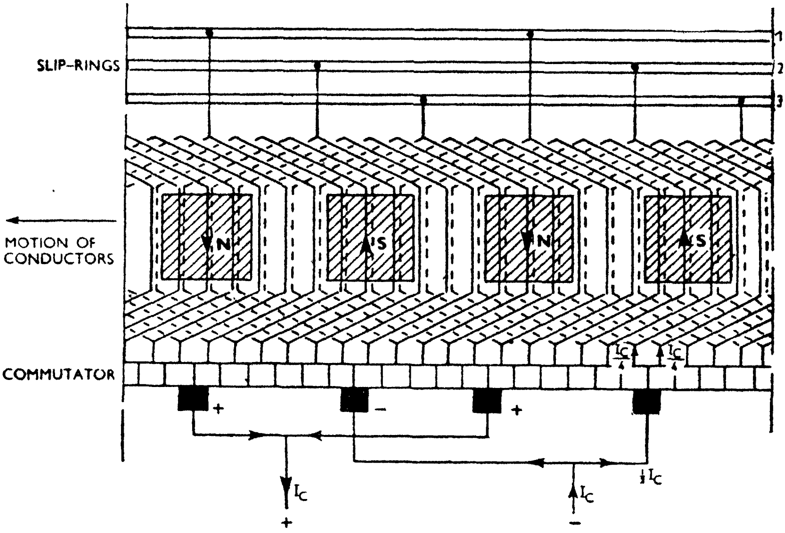
As a simple example, Fig. 3 represents a 4-pole lap-wound or parallel-wound armature winding in twenty-four slots, tapped for three phases. (In an actual machine there are usually more slots than this.) Each slip-ring is connected to two diametrically opposite tapping points in the winding and the electrical angle between two adjacent tapping points is 120 deg.

TABLE I

Type	*No. of slip-rings*	*Angle between adjacent tapping points*
Single-phase	2	180 electrical deg.
Two-phase (four-phase)	4	90 ,, ,,
Three-phase	3	120 ,, ,,
Six-phase	6	60 ,, ,,
Twelve-phase ..	12	30 ,, ,,

On the A.C. side the machine is precisely the same as a mesh-connected three-phase synchronous motor (or alternator) with rotating armature.

In general, the angles, in electrical degrees, between successive tapping points to the different slip-rings depend on the number of rings as shown in Table I (360 electrical deg. is the angle corresponding to two pole pitches).



DEVELOPED DIAGRAM OF A 4-POLE LAP WINDING

Fig. 3. In the example illustrated here, the winding is carried in twenty-four slots and tapped for three phases. Full lines represent conductors in top layer and broken lines conductors in bottom layer, there being two layers in each slot. Successive tapping points are 120 electrical degrees, that is, one-third of two pole pitches apart. This gives two connections to each slip-ring from points in the winding always at the same potential. The paths taken by the direct current are indicated in the diagram, there being as many parallel paths as there are poles.

Supplying Multi-phase Machines

Six- and twelve-phase machines can be supplied from a three-phase system by the aid of suitable transformers and are used because they have better characteristics and higher efficiency than three-phase machines. Single-phase rotary converters are very seldom used.

It is important to realize that in a rotary converter the direct current flows in the direction of the generated e.m.f., whereas the A.C., entering the slip-rings, flows against the e.m.f., being driven by the supply voltage. Both A.C. and D.C. flow in the same winding.

Now, in any single armature conductor the generated e.m.f. produces the D.C. and acts as the back e.m.f. against the A.C. Consequently, the driving and generated currents are in opposite directions. The *resultant* or actual current is their difference at any instant.

Except in the case of the single-phase machine, this results in reduced average heating of the conductors, compared with that which would be produced if the machine were driven as an ordinary D.C. generator by a separate motor or engine.

Less Pronounced Reaction

For this reason a polyphase (many phase) rotary converter is smaller and less costly than a D.C. generator of the same output. A further advantage is that armature reaction, that is, the magnetic effect of the armature currents, is less pronounced. These advantages are enhanced as the number of phases is increased and accounts for the wide use of six- and twelve-phase types.

The output voltage on the D.C. side bears a definite theoretical ratio to the R.M.S. input voltages on the A.C. side, depending on the number of slip-rings. With the machine on load there is a slight departure from this theoretical ratio, due to internal volt-drop, brought about mainly by resistance of the armature winding and to volt-drop at the brushes.

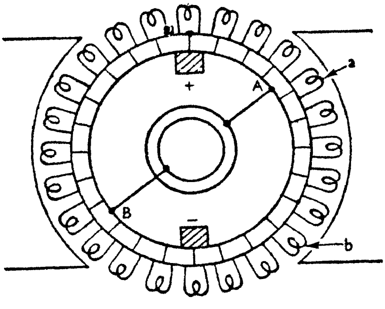


Fig. 4. Diagrammatic representation of a 2-pole single-phase rotary converter. Slip-rings are connected to diametrically opposite points in the winding. A ring-type winding is illustrated, as it simplifies theoretical considerations. Brushes are at neutral points on the commutator, and the alternating voltage between slip-rings reaches its peak value when tapping points coincide with the D.C. brush positions. Therefore, peak value of alternating voltage is equal to D.C. voltage.

Although the single-phase machine is uncommon, its consideration will help us to understand more easily the action of polyphase machines. Fig. 4 represents, in diagrammatic form, a 2-pole single-phase rotary converter. It illustrates the electrical but not the mechanical conditions.

For convenience, twenty-four armature coils are shown in ring formation as used in early machines with ring-wound armatures, and the brushes are shown on the inside of the commutator. The two slip-rings are shown connected to diametrically opposite commutator segments, *A* and *B*. In an actual machine the tappings are at the other end of the armature winding.

Position of Brushes

Now, the positive and negative brushes are placed midway between the poles, that is, at the *neutral points* on the commutator where no potential difference exists between adjacent segments. At the same time, the maximum voltage given by the machine occurs between neutral points of opposite polarity, being the output voltage V_C between brushes on the commutator or D.C. side.

There are two paths or circuits in parallel between the brushes, each containing twelve coils. So the voltage between brushes is equal to the sum of the e.m.f.'s in all coils in series in one branch. The e.m.f. in each coil is alternating, and as the coils are evenly spaced by an angle $\frac{1}{12}$th of 180 deg., or 15 deg., the e.m.f.'s of successive coils are out of phase by 15 deg.

The total voltage between positive and negative brushes is equal to the *vector sum* of e.m.f.'s in the twelve coils in either branch. The vectors are added one on the end of the other and so give the diagram of Fig. 5, in which the vectors of one branch lie on a semicircle.

The circle would be completed by including the vectors of the other branch. When there are very many coils and slots the vectors are correspondingly numerous and short, and the diagram approaches more closely to an actual circle.

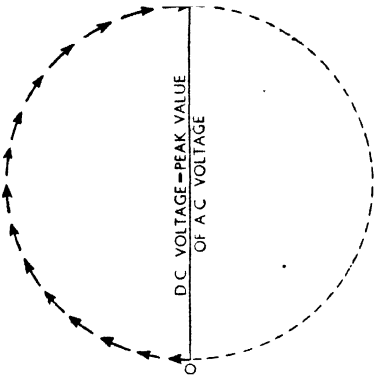


Fig. 5. Vector diagram of e.m.f.'s in the armature coils in the left-hand half of Fig. 4. As the coils are equally spaced, the successive e.m.f.'s are out of phase by equal angles, and the vectors, therefore, form a 24-sided polygon. The phase angle between e.m.f.'s in adjacent coils is 360/24 = 15 deg. The peak value of alternating voltage between slip-rings is given by the diameter of the circle enclosing the polygon of vectors and this is also the D.C. voltage.

Voltage Ratios

Referring again to Fig. 4, when the tapping points *A* and *B* happen to be midway between the poles, that is, at the neutral points where the brushes are, the alternating voltage between the slip-rings has its peak value. This is equal to the voltage between the brushes on the commutator and is represented by the diameter *PQ* of the circle in Fig. 5. We have, then, for a single-phase machine:

Peak value of alternating voltage = direct voltage.

If V is the R.M.S. value of the alternating voltage, the peak value, assuming a sine wave, is $\sqrt{2}V$, so that

$$\sqrt{2}V = V_C, \text{ or}$$

$$V = \frac{V_C}{\sqrt{2}} = 0{\cdot}707 V_C, \text{ and}$$

$$\frac{V}{V_C} = 0{\cdot}707.$$

If we imagine the machine to have no losses, the power output is equal to the input, so that,

$$V_C I_C = VI \cos \phi,$$

where $\cos \phi$ is the power factor on the A.C. side.

As in the case of a synchronous motor, the power factor depends on the excitation. At unity power factor, $V_C I_C = VI$ and, therefore:

$$\frac{I}{I_C} = \frac{V_C}{V} = \sqrt{2} = 1{\cdot}414.$$

The R.M.S. value of the A.C. is, therefore, $\sqrt{2}$ times the D.C. and the peak value of the A.C. is $\sqrt{2} \times \sqrt{2}\, I_C = 2I_C$.

The three-phase machine has three slip-rings and three tappings per pair of poles. Fig. 6 refers to the same 24-coil arrangement represented in Fig. 4 and the circle of voltages is given on the right. Here, again, the diameter *PQ* of the circle represents the D.C voltage at the commutator.

Peak Values

The *peak values* of the alternating voltages between the tapping points *AB* and *C* in the winding are given by the lines *AB*, *BC* and

CA in the voltage circle, to the same scale as the D.C. voltage *PQ*.

Now, *AB* is $\sqrt{3}/2$ times *PQ*. So, if *V* is the R.M.S. voltage between slip-rings, the peak value is and, therefore, $\sqrt{2}V = \sqrt{3}/2$ where V_C is the D.C. voltage *PQ*. The ratio of slip-ring to commutator voltage for the three-phase machine is, therefore,

$$\frac{V}{V_C} = \frac{\sqrt{3}/2}{\sqrt{2}} = 0{\cdot}612.$$

Current Relations

Again, assuming no losses and equating the three-phase input $\sqrt{3}VI$ (at unity power factor) to the D.C. output $V_C I_C$, we have $V_C I_C$, or

$$\frac{I}{I_C} = \frac{1}{\sqrt{3}} \times \frac{\sqrt{2}}{\sqrt{3}/2} = 0{\cdot}943.$$

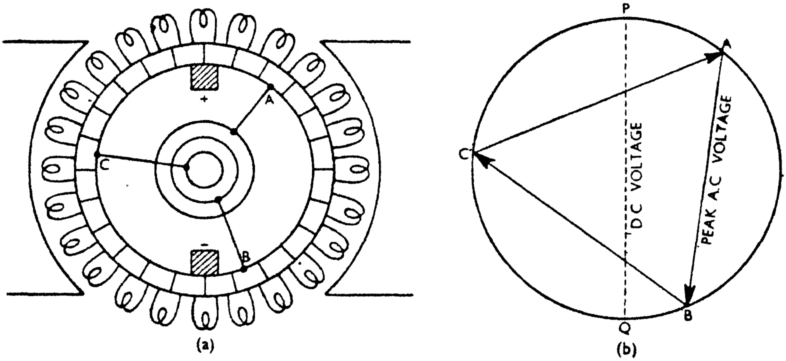
By applying the same methods to machines with other numbers of phases or slip-rings we can find the theoretical voltage and current ratios from the voltage circles. Values are given in Table II for the most usual practical cases.

TABLE II

Type	*Line voltage ratio*	*Line current ratio* I/I_C
Single-phase	0·707	1·414
Three-phase	0·612	0·943
Two-phase or Four-phase	0·500	0·707
Six-phase	0·354	0·471
Twelve-phase	0·183	0·236

The current in any armature coil is the difference between the A.C. and D.C. components at any instant. The D.C. is reversed at regular intervals by the commutator and gives a wave of rectangular form, assuming the reversal to be instantaneous. The A.C., on the other hand, is assumed to be a sine wave.

Let us consider a single-phase machine, as it presents the simplest case. An armature coil ***next to a tapping point***, such as (*a*) in Fig. 4, has its peak value of A.C. just as that coil passes a D.C. brush, if



(a) (b)

THREE-PHASE ARRANGEMENT

Fig. 6. (a) Two-pole winding tapped for three slip-rings. (b) Voltage diagram giving the D.C. voltage *PQ* and the peak values *AB*, *BC*, and *CA* of the voltages between slip-rings. As the D.C. brushes are fixed, *PQ* is stationary, but the triangle *ABC* giving the A.C. voltages rotates in unison with the armature. Lines joining the tapping points *A*, *B* and *C* in diagram (a) correspond to those in (b), and the line joining the D.C. brushes corresponds to *PQ*.

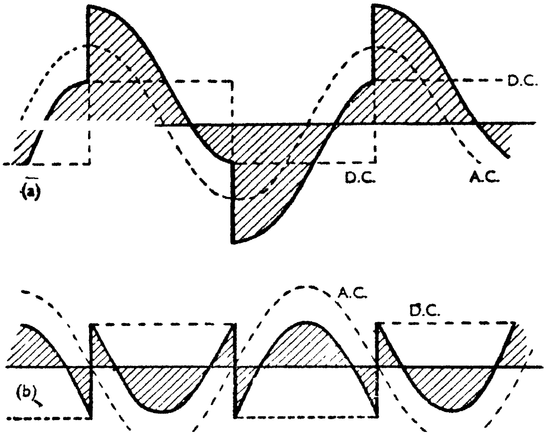


Fig. 7. Illustration shows the theoretical current wave forms for a single-phase converter. (a) Currents in coil *a*, adjacent to a tapping point, in Fig. 4. (b) Currents in coil *b*, midway between tapping points. Coil *a* is heated to a greater extent than coil *b*.

there is no angle of lag or lead. So the D.C. in the coil concerned reverses just as the A.C. passes through its maximum value. The D.C. and A.C. waves, therefore, have the relative positions shown in Fig. 7a.

We have already seen that for the single-phase machine the peak value of the A.C. is twice as great as the D.C. This applies to the coil currents as well as the line currents, since each coil carries half the D.C. and half the A.C. Their difference gives the resultant or actual coil current, which has the peculiar form shown.

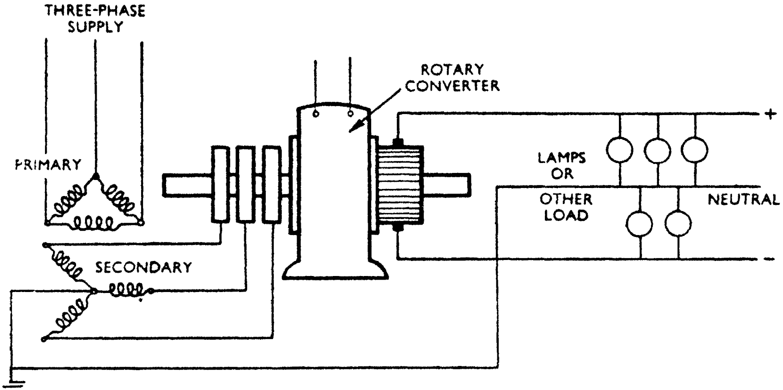
A.C. at Zero Value

On the other hand, the A.C. in a coil such as (*b*) in Fig. 4, *midway between the tapping points* passes through a zero value just as the D.C. in it is reversed. The A.C. and D.C. waves, and their resultant, are as shown in Fig. 7b. It will be noted that the actual currents in the coils *a* and *b* have different wave-shapes. The wave forms of the currents in all the intermediate coils are different again.

The power expended in heating any one coil is equal to the *mean square value* of the current multiplied by the coil resistance. The mean square value can be calculated or found graphically, and the overall or average heating of all coils in rotary converters with different numbers of phases have been worked out and compared with the heating obtained when the machine is used as an ordinary D.C. generator. These relative values are set out in Table III. The

TABLE III

	D.C. generator	*Single-phase*	*Three-phase*	*Two-phase or four-phase*	*Six-phase*	*Twelve-phase*
Mean relative heating *H*	1	1·38	0·56	0·38	0·27	0·21
Normal output or rating $1/\sqrt{H}$	1	0·85	1·33	1·62	1·92	2·18



CONNECTIONS FOR THREE-WIRE D.C. OUTPUT

Fig. 8. Circuits of a three-phase rotary converter arranged for supplying a three-wire D.C. system, with middle or neutral wire earthed.

second line in the table gives the relative outputs at which the various machines will run with the same heating and temperature rise as a D.C. generator of the same size. As regards losses, the single-phase machine is clearly the worst, whereas the twelve-phase machine is the best, so far as the table goes. A six-phase machine will give nearly twice the output, and a twelve-phase machine a little more than twice the output of a D.C. generator of the same size.

Slip-ring Supplies

These figures make it abundantly clear why six- and twelve-phase rotary converters are built. In all cases, the slip-rings are fed from the secondary windings of transformers; six-phase and twelve-phase transformers, supplied from a three-phase system, are not much more expensive than three-phase transformers.

Three-phase converters are supplied from the normal type of three-phase transformer, or three single-phase transformers. Various arrangements are satisfactory, such as mesh-connected primary and star-connected secondary (Δ/Y). This connection has the advantage of providing a neutral point for earthing the system or enabling the converter to feed a three-wire D.C. system, as illustrated in Fig. 8. If no neutral point is needed, Y/Δ or Δ/Δ connection of the transformer windings is satisfactory. Y/Y connection is not advisable, as it leads to undesirable effects in the transformers.

The transformers are designed to give at the slip-rings the voltages

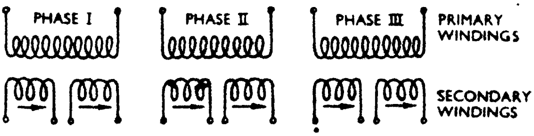
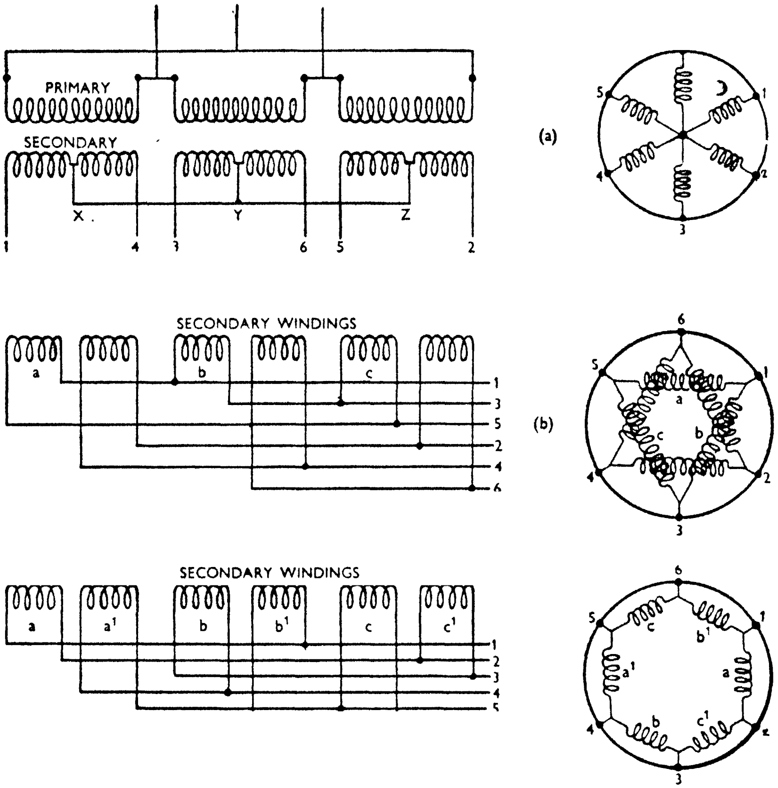


Fig. 9. Transformer group suitable for conversion from three-phase to six-phase. Two equal secondary windings are associated with each primary phase winding

mutator brushes in accordance with the voltage ratios in Table II, due allowance being



METHODS OF SUPPLYING A SIX-PHASE CONVERTER

Fig. 10. (a) Double-star connection. If no neutral point is required the connections between *X*, *Y* and *Z* can be omitted. This gives diametrical connection and a single secondary winding per phase is sufficient. (b) Double-mesh connection. (c) Hexagonal connection. The circles on the right represent the armature winding of the converter and the numbered points the corresponding slip-rings.

made for volt-drop within the machine and transformer when loaded.

Six-phase output from transformers fed from a three-phase supply is easily obtained by having two similar secondary windings to each primary, as shown in Fig. 9. There are several ways of connecting the six secondary windings to supply the six slip-rings of the converter, such as (a) double-star or diametrical, (b) double-delta, and (c) hexagonal or ring. These are all shown in Fig. 10, where, for convenience, the slip-rings are represented by the points marked 1, 2, 3, 4, 5, and 6, in order round a circle. The circle represents the armature winding as in Fig. 6.

Twelve-phase rotaries are usually of large size, supplied from a high-voltage three-phase system. Different transformer arrangements are possible. A combination of double-star and double-delta, which has four secondary windings to each primary, gives the advantage of a neutral point, and is shown in Fig. 11a.

A simpler arrangement, but giving no neutral point, uses the same transformer as in Figs. 9 and 10, but connected as in Fig. 11b. Though simpler, this arrangement gives slightly different currents in the sections of the armature winding on each side of a tapping point. The result is a slight increase in losses.

The general problems of starting a rotary converter are in all respects the same as those of a synchronous motor, already considered in Chapter 8. The machine has to be run up to speed and synchronized.

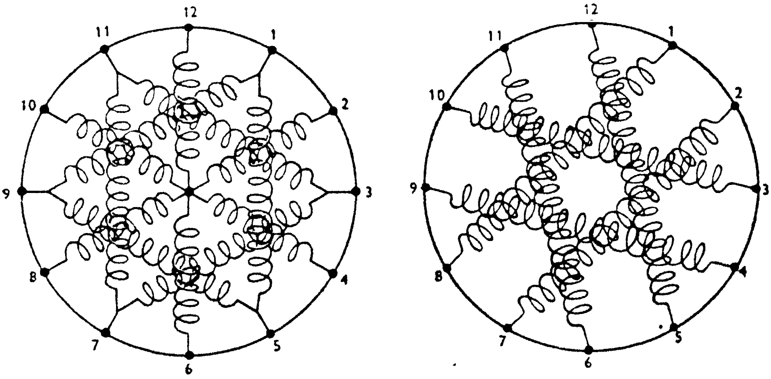
Starting Gear

When a D.C. supply is already available, as when the machine is to be paralleled with others already running, starting can be effected from the D.C. side, through a normal D.C. motor starting gear. When the speed is correct and the slip-ring voltages are in phase with the corresponding secondary voltages of the transformer, as indicated by a synchroscope, the main switch on the A.C. side may be closed. This is usually done on the primary side of the transformer.

Starting from the A.C. side is done exactly as for a synchronous motor, either through transformer tappings or by means of a small pony motor on the shaft. As the converter is self-excited it is possible for the exciting current to be in either direction when synchronism is reached.

The D.C. brushes may, therefore, have the wrong polarity for connecting to the bus-bars. When the polarity happens to be wrong, as indicated by a moving-coil voltmeter, it can be corrected by "slipping a pole." The speed is allowed to drop very slightly until the armature has slipped back by one pole pitch.

In an ordinary D.C. generator the voltage is raised by increasing the field strength. In the rotary



(a) (b)

Fig. 1. TWELVE-PHASE CONNECTIONS OF SECONDARY WINDINGS
giving n (a) Gives the advantage of a neutral point. (b) Simpler arrangement, but connected: neutral point. The primaries (not shown) may be either mesh or star winding. Th All coils with parallel axes are associated with one primary phase axes represent voltage vectors, and numbered points slip-rings

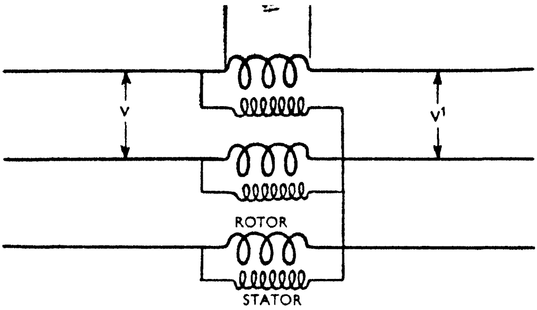


Fig. 12. Voltage regulation of a rotary converter by means of an induction regulator. This is like an induction motor with a wound rotor which, however, remains stationary. Its angular position relative to the stator can be altered by a worm-and-wheel drive. The stator is connected across the three-phase supply, and each phase of the rotor winding is in series with one line. The constant rotor voltage is added vectorially to the supply voltage per phase, the resultant voltage depending on the position of the rotor.

converter, however, the voltage at the D.C. brushes depends alone on the voltage applied to the slip-rings on the A.C. side nearly, but not quite, in accordance with the ratios given in Table II. The slight departure from the theoretical ratio is due to resistance in the armature circuit.

Varying the exciting current merely varies the power factor on the A.C. side. As explained for the synchronous motor, excess excitation causes the machine to take a leading component of wattless current in addition to the power component. Under-excitation, on the other hand, causes a lagging wattless current to flow. In either case, the wattless current is just sufficient to maintain the actual field strength unchanged, through the action of armature reaction.

If the voltage on the A.C. side is kept constant, that on the D.C. side falls somewhat as the load increases, even if the machine is compound wound. So to maintain a constant D.C. voltage, or to get a slightly rising voltage, it is necessary to raise continuously the alternating voltages applied to the slip-rings as the load increases.

There are several ways of doing this, the most usual being either (*a*) by means of an induction regulator in the three-phase supply to the main transformer(s), or (*b*) by means of series reactors in the A.C. leads, the machine itself being compound-wound so D.C. excitation increases as load rises.

Induction Regulator

(*a*) An induction regulator is constructed like a three-phase induction motor with a wound rotor. The stator windings form the primary and are connected across the supply. The rotor is not free to rotate continuously but it can be revolved through one pole pitch by a worm drive automatically or manually operated.

Each phase winding of the rotor is connected in *series* with the A.C. supply, and gives a constant voltage about equal to the total change of voltage required on the A.C. side.

Each secondary or rotor voltage is added vectorially to the phase-to-neutral voltage of the supply, or $\sqrt{3}$ times the rotor voltage to the line-to-line voltage, the resultant depending on the phase angle between the original and the added voltage. This is shown in Fig. 12.

(*b*) The series reactance method (Fig. 13) is based on the fact that the power factor of the machine depends on the degree of excitation. With "normal" excitation there is no wattless current, with under-excitation a lagging wattless current flows, and with over-excitation a leading wattless current is taken, in addition to the power component of current. The machine is compounded so that as the load rises the total excitation increases and advances the phase angle of current with respect to voltage.

With reactance in series, the voltage across the reactor is in quadrature with the current and is added vectorially to each phase voltage at an angle depending on the degree of total excitation, which in turn depends on the load current on the D.C. side.

The shunt excitation is adjusted so that at no-load the machine takes a small lagging component of current. A rise of load increases the excitation and so advances the phase angle of the current, which also increases in magnitude. The voltage across each reactor, therefore, advances in phase and at the same time increases in value.

At full-load the excitation is greatest and the current leads the slip-ring voltage, which may then be higher than the supply voltage. The general scheme is illustrated in Fig. 13.

Mercury-arc Rectifier

A mercury-arc rectifier consists essentially of a number of carbon electrodes enclosed in a vessel from which the air has been removed, and at the bottom of which is a pool of mercury. The vessel may be either a glass bulb or a steel tank.

The essential characteristic of this arrangement is that an electric arc can be formed between a carbon electrode and the pool of mercury, provided the carbon is electrically positive with respect to the mercury, the current flowing through the mercury vapour produced by the heat of the arc. If the carbon is negative, no arc can be formed, even if mercury vapour is present.

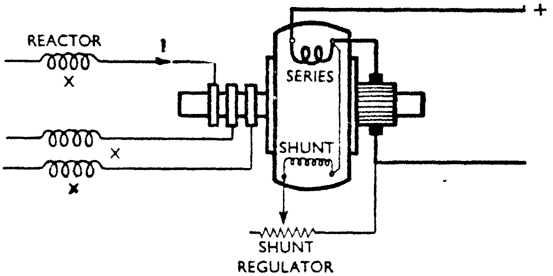


Fig. 13. Regulation by series reactance. A reactor *X* is connected in series with each line, or, alternatively, each secondary winding of the transformer is designed to have a suitable reactance. The reactive voltage is 90 deg. in advance of the current in each reactor. The machine itself is compounded so that as the load rises the total excitation is increased, causing the phase angle of the current to advance. The reactive voltage is, therefore, added vectorially to the slip-ring voltage at an angle depending on the current on the D.C. side of the machine and so alters the total voltage.

In other words, current will pass freely through mercury vapour from carbon to mercury, but no current can flow in the reverse direction. This valve action forms the basis of the mercury-arc rectifier for converting from A.C. to D.C.

An example of a simple single-phase glass-bulb rectifier is illustrated in Fig. 14, in which there are two carbon electrodes or *anodes*, 1 and 2, connected to the secondary winding of a transformer. The D.C. "load," such as a battery to be charged, is connected between the mercury *cathode* and the centre tapping of the transformer secondary winding.

Current flows one half-cycle and from the other anode to the cathode for the next half-cycle, and both half-waves of current flow in the *same direction* from the cathode through the load and back to the centre tap of the transformer.

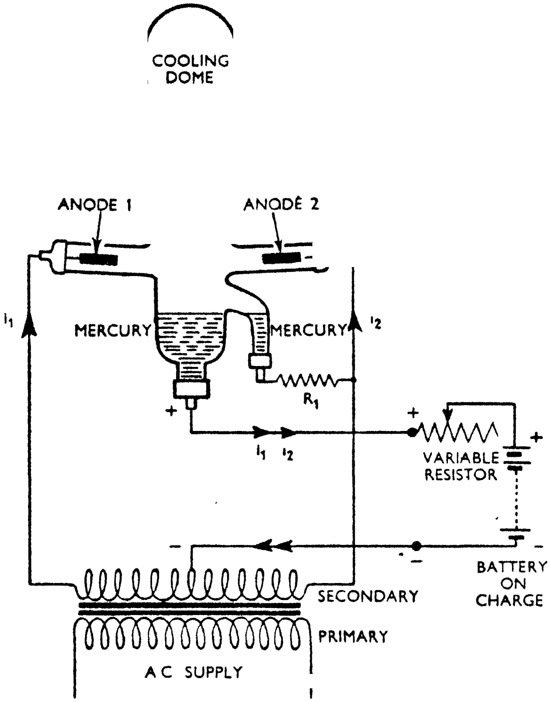


Fig. 14. Single-phase mercury-arc rectifier supplied from transformer with centre-tapped secondary winding. The mercury pool constitutes the positive terminal and the transformer centre-tap the negative terminal of D.C. output circuit. The bulb is carried in a rocking cradle and starting is effected by tilting it clockwise until the mercury in the main reservoir joins that in the starting arm. On returning the bulb to the vertical position, the bridge of mercury breaks and a temporary arc is formed, generating sufficient mercury vapour for the main anodes 1 and 2 to come into action.

The paths taken by the current are shown in Fig. 14. The current is in effect switched or "commutated" from one anode to the other every half-cycle. The two anodes have opposite polarity relative to the centre tap of the secondary winding, and the arc always passes to the mercury from the anode which happens to be positive.

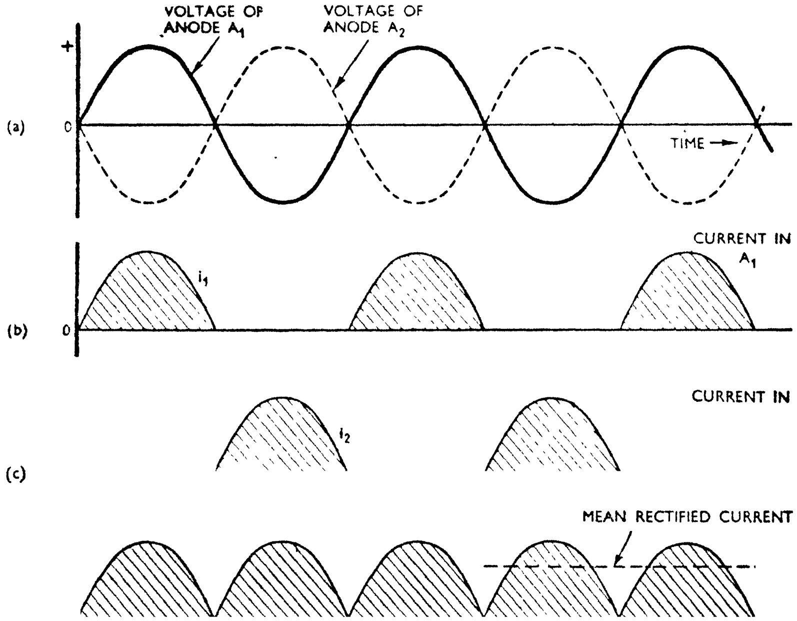
In Fig. 15, the sine waves at (a) represent the voltages of the anodes with respect to the centre tap. If the D.C. load consisted of a simple resistance, the currents in the various parts of the circuit would be represented by the curves at (b), (c) and (d) in Fig. 15. Each half of the transformer secondary winding carries a pulsating direct current from the centre tap outwards, whilst the primary winding carries a normal A.C. In the D.C. output circuit, both half-waves of current are in the same direction, full-wave rectification being obtained.

When a battery of accumulators is being charged from the rectifier, the peak voltage given by each half of the transformer secondary must be considerably greater than the e.m.f. of the battery, which is connected, through a suitable regulating resistance, with its positive terminal to the cathode and its negative terminal to the centre tap of the transformer. Current will flow from either anode only when its positive voltage exceeds the e.m.f. of the battery, the conditions being clearly shown in Fig. 16. The current curves shown in both Figs. 15 and 16 are based on the assumption that there is no inductance in the circuit and the volt drop across the arc itself is assumed to be negligible.

"Igniting" the Bulb

No current can flow unless the bulb contains mercury vapour, and no mercury vapour will exist until an arc is formed. For this reason, special means must be provided for producing the mercury vapour or "igniting" the bulb before the rectifier can be set in action.

In the arrangement of Fig. 14 this is done by tilting the bulb clockwise until the mercury in the



CURVES ILLUSTRATING ACTION OF RECTIFIER

Fig. 15. (a) Voltages of anode A_1 and anode A_2 with respect to the centre tap of the transformer. (b) and (c) Current impulses in anode A_1 and anode A_2 respectively. (d) Current in the D.C. output circuit, assuming no smoothing arrangements to be included, and that the load is a simple resistance.

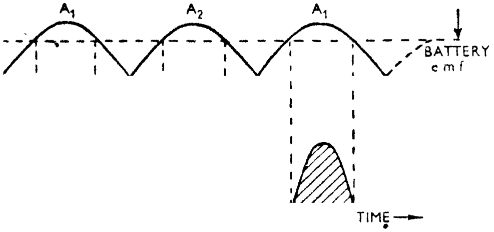


Fig. 16. Action of the single-phase rectifier when the D.C. load is a battery to be charged, in series with a regulating resistance, as in Fig. 14.

main reservoir joins that in the starting arm. This allows *alternating* current to flow from the right-hand side of the transformer winding, round the circuit formed by the ignition resistance R_1 and the "load" across the output terminals.

When the bulb is returned to its normal position the bridge of mercury parts, causing a temporary arc to be formed. This generates sufficient vapour to allow the anodes 1 and 2 to pass current in turn to the cathode and so to maintain the supply of mercury vapour. A disadvantage is that the bulb will not ignite unless the D.C. load is in circuit, and a better method, with automatic starting, is explained further on.

The vapour condenses back into liquid mercury on the inside of the cooling dome and trickles back into the mercury pool. The heat generated in the bulb is in this way dissipated through the wall of the bulb. The anodes are mounted in projecting arms or tubes to reduce the danger of an arc forming between them.

Mercury-arc Efficiency

A notable feature of the mercury-arc is that the anode-to-cathode resistance varies in almost inverse ratio to the current. If the current is doubled the resistance is halved, and so the volt-drop between anode and cathode is practically the same for all values of current. It is between 20 and 30 V.

With a sine wave of voltage input the mean rectified voltage of the single-phase rectifier would be $\frac{1}{1\cdot11}$, or 0·9 times the R.M.S. voltage between either anode and the centre tap of the transformer, providing there was no internal volt drop. The number 1·11 is the form factor of a sine wave (Chapter 7). So if V is the R.M.S. voltage of each half of the transformer secondary winding and if the volt drop in the arc is taken as 25, the D.C. output voltage would be $(0\cdot9 \times V) - 25$, approximately.

Internal Losses

If there were no internal losses, the mean D.C. voltage output would be 0·9 × V and the efficiency would be 100 per cent. With 25 V drop in the arc the efficiency of the rectifier itself, apart from the transformer, is

$$\frac{(0\cdot9 \times V) - 25}{0\cdot9 \times V} \times 100 \text{ per cent.}$$

The size of the bulb is determined entirely by the *current* it has to carry and is quite independent of the output or input voltages—in all circumstances, there is only about 25 V drop across the rectifier. So the same bulb could be used to give 50 A output at 100 V, or 50 A output at 1000 V.

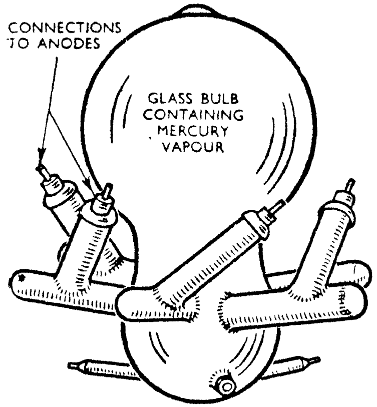


Fig. 17. Six-phase glass-bulb rectifier. Main anodes are in sloping tubes attached to six arms projecting from the bulb. This is to eliminate danger of an arc forming between two anodes of opposite polarity, as would be the case if the anodes were mounted inside the main bulb. Small electrodes near the bottom are for ignition and excitation, their details being shown in Fig. 21.

Firstly, the rectifier efficiency would be $\frac{100-25}{100} \times 100 = 75$ per cent, whereas in the second it would be $\frac{1000-25}{1000} \times 100 = 97{\cdot}5$ per cent.

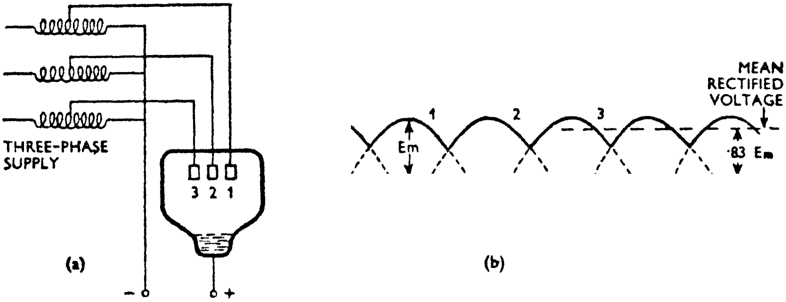
The higher the voltage the better the efficiency. These figures do not include transformer losses, which lower the overall efficiency. A good transformer has itself an efficiency of 96 per cent or so.

By the use of more than two anodes, on a supply with a corresponding number of phases, a much more uniform D.C. output voltage is obtained—the larger the number of anodes or phases the smoother is the output voltage. Except for small sizes, glass-bulb rectifiers usually have six main anodes supplied from a three-phase to six-phase transformer, as described in connection with the rotary converter. Large steel tank rectifiers have twelve phases.

Auxiliary Anodes

Besides the main anodes there are usually two auxiliary anodes supplying a small permanently connected load and supplied from an auxiliary winding on the main transformer, the operation being the same as for the single-phase rectifier. The purpose is to keep the rectifier excited when the main D.C. load is switched off. Circuit details are given in Fig. 21.

A six-phase glass-bulb rectifier is illustrated in Fig. 17. A three-phase bulb is similar, but has only



MAIN CIRCUIT OF A THREE-PHASE RECTIFIER

Fig. 18. (a) Input circuit arrangement of a three-phase rectifier fed from an auto-transformer, auxiliary circuits being omitted. The arc passes from one anode at a time to mercury cathode, always from the most positive anode. With sine waves of applied voltage, rectified wave is as shown by full-line curve at (b).

three main anode arms instead of six.

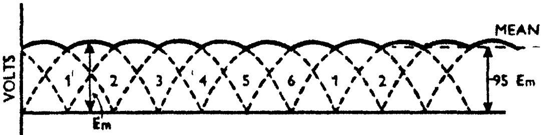


Fig 19. Rectified output voltage obtained from six-anode rectifier. The voltage ripple is much less pronounced than with three anodes.

The main circuits of a three-phase rectifier fed from an auto-transformer are represented diagrammatically in Fig. 18a. The alternating voltages differ in phase by 120 deg., or a third of a cycle, and the arc always passes between the most positive anode and the mercury, only one anode at a time being in action. So each anode carries current for a third of a period, and the D.C. output voltage varies in the manner shown by the full line or "envelope" curve of Fig. 18b. The negative half-waves of alternating voltage are left out, as they play no part. The D.C. voltage (between cathode and neutral point) fluctuates between the peak value of the alternating voltage per phase and half this value.

The mean value of the D.C. voltage is about 83 per cent of the maximum A.C. voltage, neglecting volt drop in the arc.

The conditions for plain six-phase working, with six anodes, are given in Fig. 19. The D.C. voltage is seen to fluctuate much less than for three-phase. It varies between maximum alternating voltage and 86·6 per cent of this, the mean value being 95·5 per cent of maximum.

For any polyphase rectifier, the secondary windings of the input transformer must be so connected as to provide a neutral point, for this constitutes the negative terminal of the D.C. output circuit. Suitable methods of

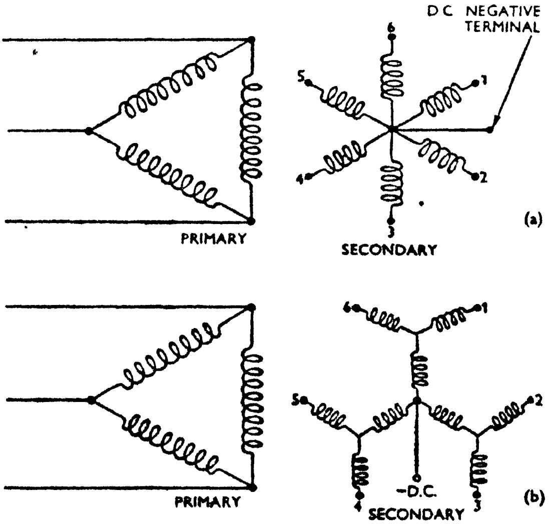


Fig. 20. Two methods of transformer connection for obtaining six-phase operation from a three-phase supply. (a) Simple six-phase or double-star connection. (b) Six-phase branched star or fork connection. In this, each outer prong of the fork carries the current for one-sixth of a period, whilst the innermost branches carry current for one-third of a period. A reduction of losses is obtained in this way, compared with method (a). Both systems provide the neutral point required as negative D.C. terminal.

connection for six-phase rectifiers are shown in Fig. 20. At (a) is shown the same double-star connection explained in connection with the six-phase rotary converter. The transformer windings are drawn in such a way that the axis of each represents the corresponding voltage vector.

Fork Connection

Another arrangement, known as the six-phase branched star or fork connection, is shown at (b) in Fig. 20. There are three secondary windings associated with each primary. Here, again, the winding axes represent corresponding voltage vectors. The numbered terminals are connected to the anodes in the same order round the rectifier bulb and the numbers represent the order of firing.

Tilting the bulb for starting the arc, as previously described, is not practical except for very small rectifiers, and there are better methods, completely automatic, for the larger sizes. A widely used system is illustrated in Fig. 21.

The main transformer (not shown) has an extra 110 V secondary winding on one phase and this supplies a small ignition and excitation transformer which has two secondary windings, one with centre tapping, to supply current to the auxiliary excitation anodes, and one to supply the ignition circuit.

The ignition arm near the bottom of the bulb contains a spring-mounted iron armature, at the end of which is attached the carbon ignition anode. This is normally just clear of the mercury. Outside the ignition arm and just below the iron armature is a small electromagnet which, when excited, pulls the armature down (acting through the glass) and dips the anode into the mercury.

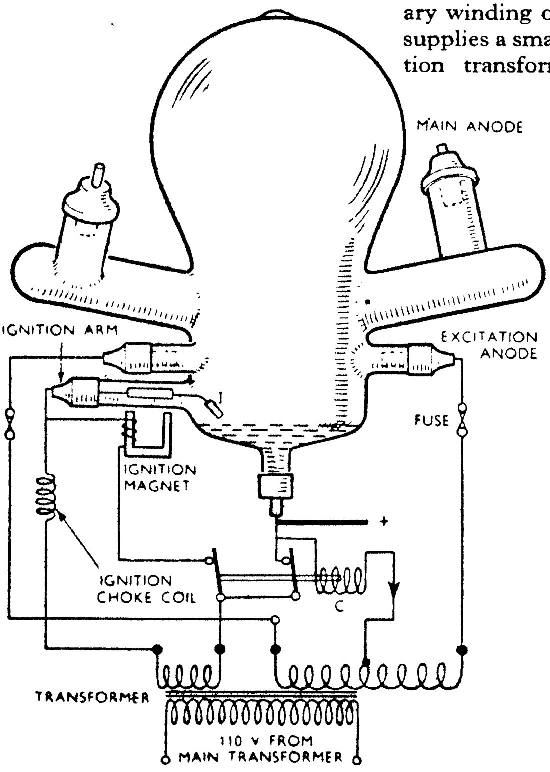
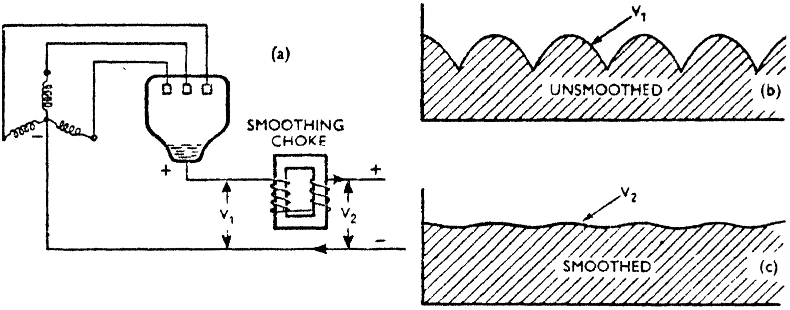


Fig. 21. Ignition and excitation circuits of a fully automatic rectifier. Although only two main anodes are shown, the system applies to a rectifier with any number of phases. Starting operations explained in the text.

When the main supply is switched



EFFECT OF SMOOTHING CHOKE IN D.C. CIRCUIT

Fig. 22. Voltage ripple is reduced to an extent proportional to the inductance of the smoothing choke and to D.C. load current. (a) Introduction of a smoothing choke into circuit of a three-phase rectifier. In (b) and (c) results are compared.

on, current flows from the ignition winding of the transformer through the ignition magnet. This causes the anode to be dipped into the mercury, thus short-circuiting the ignition magnet. The latter becomes de-energized, allowing the spring to lift the anode from the mercury and so form an arc.

A supply of vapour is thereby produced and the two excitation anodes start rectifying current from the centre-tapped winding of transformer, giving full-wave single-phase rectification. The rectified current passes through the coil of a contactor relay, which has two contacts, and which disconnects the ignition circuits when the bulb is excited.

The bulb is now ready to take the main D.C. load, which can be switched on and off repeatedly if desired, for the bulb is kept excited by the excitation circuit.

Ripples in the D.C. circuits are prone to cause interference with telephone circuits, especially when rectifiers are used for railway traction service. A low-resistance coil of high inductance wound on an iron core and connected in series with the D.C. circuit provides very effective smoothing.

Inductance can be described as that electromagnetic property which opposes any change of current. The coil, therefore, has a smoothing effect on the current, not only reducing the cyclic current variations but also removing the sharp changes which occur in an unsmoothed circuit. The circuit and the effects of the smoothing coil are illustrated in Fig. 22, a three-phase rectifier being chosen, as the effects are more easily shown than for six-phase.

Transformer Design

It has been pointed out that in a plain rectifier the arc is transferred from one anode to the next, and that only one anode is active at any time. This means that in a six-phase rectifier each secondary winding of the main transformer carries the whole current for one-sixth of a period during each cycle, and the economical design of the transformer is rendered difficult.

By the use of a device known as an interphase transformer, a six-phase rectifier with double-star connection can be made to operate in such a way that the current is always divided between two anodes, each carrying half the total current for one-third of a period. This permits the use of a transformer of much more economical design.

Double Three-phase

The arrangement is shown in Fig. 23. The interphase transformer is like a centre-tapped smoothing choke with a closed iron core. The connections are such that the rectified current from *three* anodes forming a three-phase group goes through each half of the winding; one half of which, therefore, acts as a smoothing choke for the three-phase group concerned.

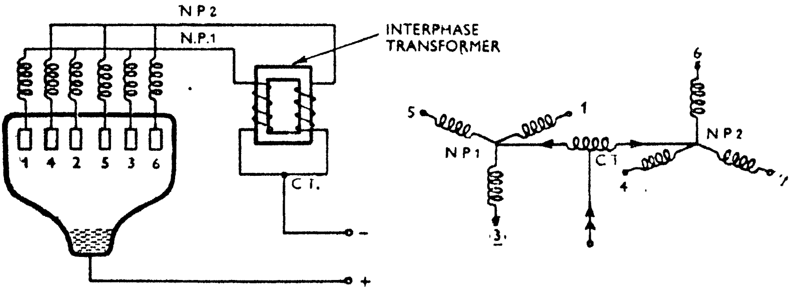
The voltage ripple which occurs across that half winding causes a corresponding e.m.f. to be induced in the other by transformer action. Thus, the ripples on one three-phase group are superimposed on the anode voltage of the other.

The net result is that the voltage waves applied to all anodes are flattened, and two anodes at a time have the same potential for about one-sixth of a period. This allows the respective currents to overlap so that each transformer secondary winding carries half the total current for one-third of a period, instead of the whole current for one-sixth of a period.

As a result, not only is a considerable smoothing effect obtained, but better and more economical loading of the transformer secondary windings is achieved. The effects of the interphase transformer are illustrated by the diagrams of Fig. 24.

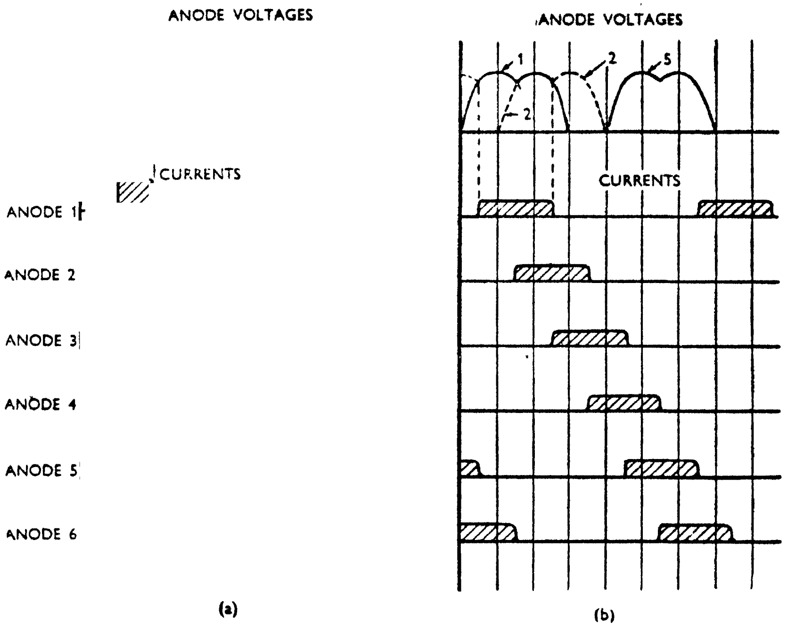
In a plain rectifier without interphase transformer, the output voltage on the D.C. side bears a more or less constant ratio to the alternating voltage between the neutral point and each anode. But as the load is raised there is an increasing volt drop in the main transformer, resulting in a reduction of output voltage more or less proportional to the load current.

The problem of voltage regulation is, therefore, much the same as



INTERPHASE TRANSFORMER IN A SIX-PHASE RECTIFIER

Fig. 23. Transformer is interposed between the two three-phase groups of the main transformer as shown in the simplified diagram on the right. The effect is to transfer by transformer action the three-phase ripple of one group on to the other, and the phase relationship is such that the voltage waves of all six anodes become flattened; a much smoother output is thus obtained and, in addition, the current impulses of successive anodes overlap. In consequence, each secondary winding of the main transformer carries less current for a longer period, resulting in lower losses and better utilization of the active material.



EFFECT ON ANODE VOLTAGE WAVE-FORM

Fig. 24. (a) Conditions without interphase transformer; (b) conditions with interphase transformer. The effect is to modify anode voltage wave-form so that over each one-sixth period two anodes at a time have the same voltage. Voltage waves of only three anodes are shown in (b) for simplicity. The current, assumed to be constant, is always divided between the two anodes at the same potential, so that current impulses overlap as shown. Since the I^2R losses are proportional to the square of current, average loss in each transformer secondary winding is halved by the use of the interphase transformer, half the current for double the time gives half the energy loss. Output is as smooth as that of a twelve-phase rectifier.

for a rotary converter, and it is necessary to regulate on the A.C. side either by the use of suitable tappings on the main transformer or by means of an induction type of regulator.

Output Voltage Drop

The interphase transformer with a six-phase rectifier causes a fairly sudden drop of about 15 per cent in the output voltage between no load and quite a small fraction of full load, about one or two per cent. This is due to the flattening of the anode voltage wave-form, but it does not present any problem if the load never falls right away to zero.

A rectifier, as we have seen from our study of the mercury-arc type, is a device which produces D.C. from an A.C. supply by allowing current to pass freely through it in one direction, whilst completely or nearly completely preventing current flow in the opposite direction. An ideal rectifier is one which presents a low constant resistance to current in the forward direction and infinitely high resistance in the reverse direction. The static

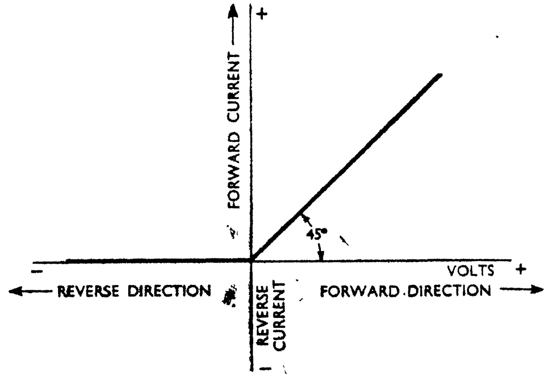


Fig. 25. Static characteristic of a theoretically perfect rectifier. The current in the forward direction is proportional to the applied voltage, but no current flows with reversed voltage.

characteristic of an ideal rectifier is shown in Fig. 25.

The current in the forward direction is proportional to the applied voltage. When the voltage is reversed no current whatever flows.

When an alternating voltage is applied to a device with these properties, current only flows during the "forward" half-cycles of voltage and the pulses, therefore, are unidirectional, being always in the same direction.

In practice, there is no really perfect rectifier. All rectifying devices have a curved voltage-current characteristic in the forward direction, indicating that the forward resistance varies with the current; and most of them will pass a comparatively very small current in the reverse direction.

Metal Rectifiers

The merit of goodness of a rectifier is determined by the ratio of reverse resistance to f

or the ratio of forward current to reverse current with a given applied voltage.

Although there are many rectifying devices in existence, including electrolytic and thermionic types, dry metal rectifiers stand in a class by themselves. They are electronic in action and, as no chemical change takes place, their life is unlimited providing they are not overheated

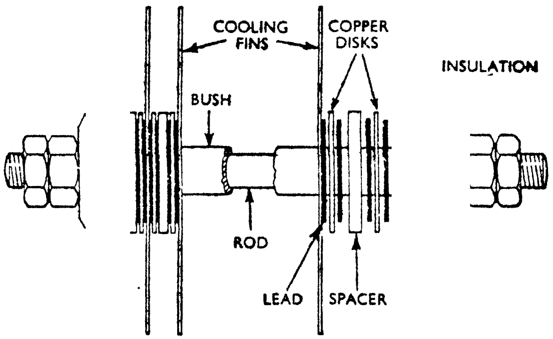


Fig. 26. Constructional details of a copper-oxide rectifier provided with cooling fins. Each copper disk, coated on one side with cuprous oxide, is pressed between two lead disks which provide good electrical contact over the whole of each surface. Alternate rectifying elements have metal spacers and cooling fins between them. All elements are insulated from the clamping rod and nuts by the insulating bush and end washers. The components of two elements are shown separated. The terminals are mounted on the cooling fins at the appropriate points

by excessive current, or broken down by excessive voltage.

There are two practical forms of metal rectifier, the copper-oxide type, which has been in use for many years, and the selenium type, a more recent development. They are somewhat alike in characteristics and have the same field of usefulness.

A copper-oxide rectifying element consists essentially of a copper disk with a thin coating of cuprous oxide on one side, produced by a carefully controlled process. The oxide film is sandwiched between the copper disk and a lead disk or washer, under a somewhat critical mechanical pressure. The lead disk is used to secure good electrical contact with the oxide film.

The rectifier depends for its action on the fact that current can flow freely from oxide to copper, but experiences very high resistance in the reverse direction.

Fig. 26 shows a number of rectifying elements in series clamped together by means of nuts on a threaded rod inside a fibre insulating bushing. At each end are insulating washers and metal plates to ensure even pressure. Metal spacers and aluminium cooling fins are interposed between the units to carry away heat generated and so increase the current rating. The cooling fins may be round or square (Fig. 27).

The number of elements in series depends on the operating voltage, about one element for each 11 V R.M.S. of the A.C. supply. The active surface area of each element depends on the D.C. to be supplied.

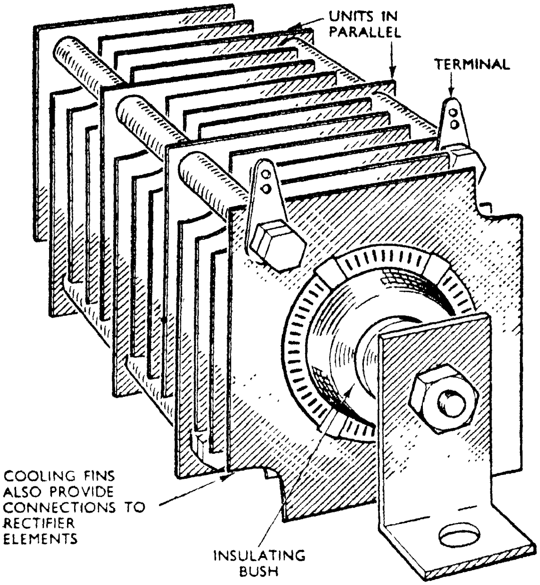
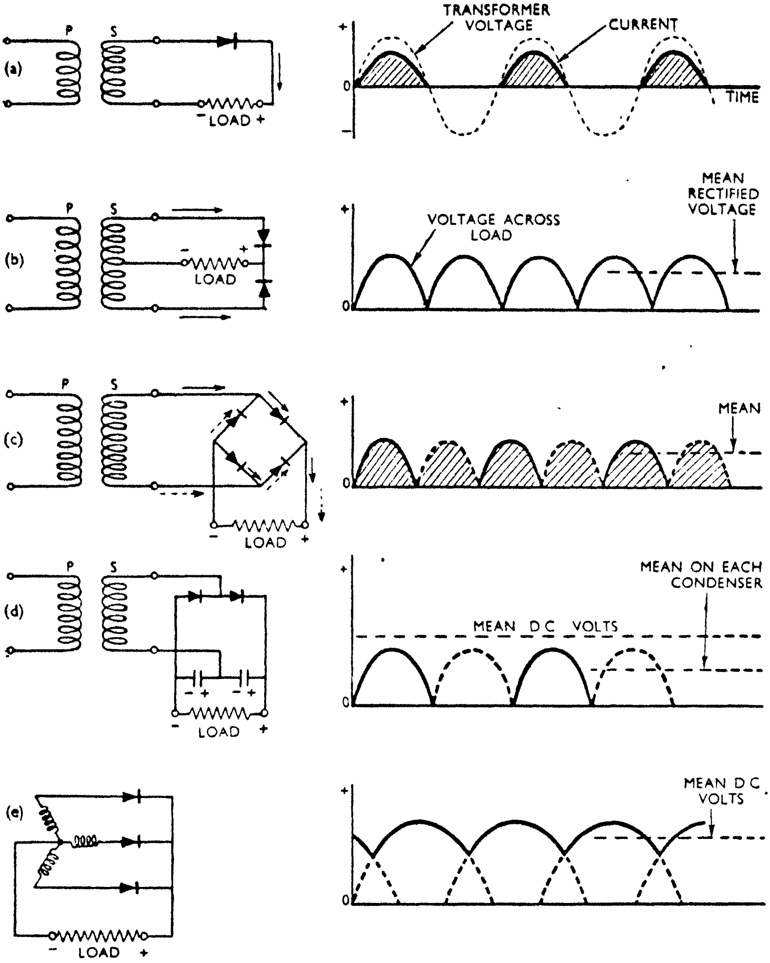


Fig. 27. Copper-oxide rectifier built into a unit for which the circuit arrangements are shown in Fig. 28c. This is a low-voltage rectifier suitable for the charging of small batteries. There are four sections and each may contain several rectifier elements in series or in parallel.

The selenium rectifier is constructed on similar lines. Each element comprises a nickel-plated iron disk coated with metallic selenium and subjected to a special heat treatment. The selenium surface is coated with a thin layer of a special alloy to provide electrical contact and distribute the current evenly.

Current can pass freely from the iron to the selenium, but in the



METHODS OF CONNECTING METAL RECTIFIERS

Fig. 28. Various methods of connecting metal rectifiers; with curves showing the nature of the rectified voltage or current in each case.

reverse direction the resistance is extremely high.

For both copper-oxide and selenium types, if a curve is drawn showing the current obtained with various applied voltages in both directions, the reverse current is so small compared with the forward current that the reverse current part of the curve almost coincides with the zero line.

There are various methods of operating metal rectifiers, the choice depending on the values of rectified voltage and current required. The rectifiers are usually built into units arranged to suit the method of connection required.

Various practical methods of connection are illustrated in the diagrams (a) to (e) in Fig. 28. In the diagrams each individual rectifier section, comprising one or more elements according to the voltage, is represented by the broad arrowhead with its point touching the short straight line. The arrow indicates the direction of current flow.

(a) Single-phase, half-wave rectification. This is the simplest arrangement, giving half-wave rectification as shown by the curve on the right. Only one half of each alternating wave of voltage is used, no current flowing during the negative half-cycle of input voltage. The method is not much used because the output voltage and current are not easily smoothed.

Single-phase Full-wave

(b) Single-phase, full-wave, with centre-tapped transformer input. The unit is built in two opposed sections, or two independent rectifiers can be used. Each half of the transformer secondary has a voltage about equal to the D.C. output voltage required. Each rectifier section has the requisite number of elements according to the voltage, and each passes a pulse of current in turn.

(c) Single-phase, full-wave, bridge connection. In this, perhaps the most widely used arrangement, four rectifier sections are employed. The special advantage over the last method is that a normal transformer, with only half the secondary voltage, is required. The four sections of the rectifier are usually built into a four-terminal unit, as illustrated in Fig. 27. The paths taken by the currents, corresponding to the positive and the negative half-waves of input voltage, are indicated by the arrows in Fig. 28c.

(d) Single-phase, full-wave, voltage doubler circuit. This is a very useful method giving a D.C. output voltage about twice as great as the transformer secondary voltage. It is eminently suitable for low-current high-voltage outputs as required by the H.T. circuits of radio receivers.

Voltage Doubling

Each of the two reservoir condensers shown is charged up by half-wave rectification to a voltage approximately equal to that of the transformer. Since the condensers are in series, the total voltage applied to the load is double that of each condenser. As the combined charge of the condensers is drained away by the load, the charge of each is replenished in turn once per cycle. An advantage is that the condensers have a partial smoothing effect on the output voltage; the lower the output current and the higher the capacitance, the smoother is the output.

(e) Three-phase rectification. This arrangement is very useful where a three-phase supply is available. Even with no smoothing arrangements there is no point at which the rectified voltage falls to zero, as it does in single-phase systems. The voltage ripple is comparatively small and has three times the frequency of the A.C. supply. Smoothing, if desirable, is much more easily achieved.

Six-phase arrangements are also possible, as explained in the section on mercury-arc rectifiers, and are employed for heavy current outputs.

CHAPTER 12

MEASUREMENT OF ELECTRICITY

ELECTRICAL MEASURING INSTRUMENTS. BASIC PRINCIPLES. MOVING-COIL AND MOVING-IRON TYPES. DYNAMOMETER PRINCIPLE. INDUCTION PATTERN. ELECTROSTATIC VOLTMETERS. THERMO-JUNCTION MOVING-COIL INDICATOR. RECTIFIER-OPERATED MOVING-COIL. VALVE VOLTMETER. GALVANOMETERS. POTENTIOMETERS AND BRIDGES. BRIDGE CIRCUITS. FREQUENCY METERS. POWER FACTOR METERS. INTEGRATING METERS. INDUCTION AND COMMUTATOR WATT-HOUR METERS. COMMUTATOR AMPERE-HOUR METERS.

ELECTRICAL measuring instruments fall into two main categories: (*a*) Instruments for measuring some electrical quantity such as volts, amperes, watts and ohms; (*b*) devices for integrating some electrical quantity against time, such as the watt-hour or kWh meter.

Operating Principles

The first group of instruments may be subdivided by the principle of operation. The simple types are moving coil, moving iron, dynamometer, induction and electrostatic; whilst the compound types, all of which employ a moving-coil indicator, are the thermo-junction, rectifier-operated, and valve voltmeter.

The simple types comprise a "movement," that is, an indicating mechanism together with a resistor and/or a reactor. The compound types incorporate the extra circuit elements mentioned in their title.

Now, to make an electrical measurement, it is necessary to take an electrical "sample," turn it into a mechanical force and measure that force. The earliest electrical instruments used a weight, and the distance that the weight was raised was a measure of the electrical force. These were termed "gravity," or "gravity-controlled," instruments. Most of the present-day measuring

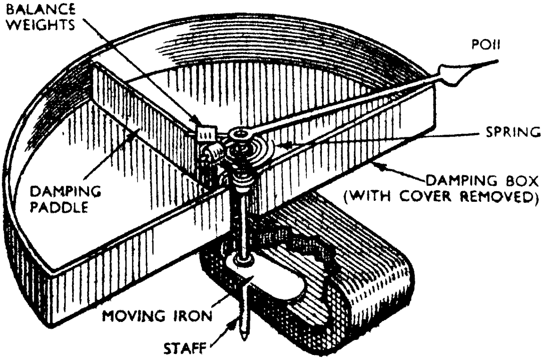


Fig. 1. Working parts of moving-iron instrument of the attraction type. Piece of iron is drawn towards centre of a coil when current is passed; to show movement clearly, instrument illustrated is a right-hand zero type.

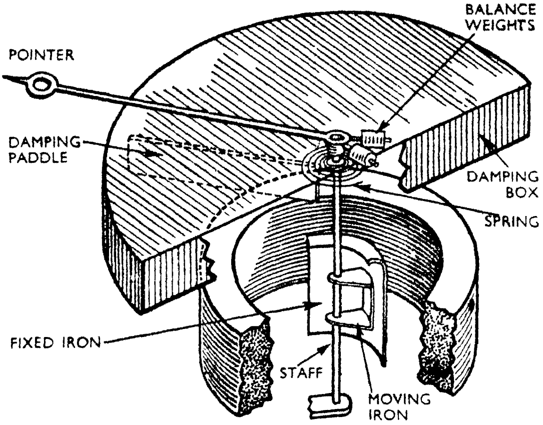


Fig. 2. Moving-iron instrument of the repulsion or "double-iron" type, where an iron strip is fixed axially inside the coil, as shown above.

instruments employ a hairspring against which the electrical force is pitted. The amount of coiling up or uncoiling of the spring is the measure of the electrical force and is normally indicated by means of an aluminium pointer attached to the moving element, and moving in front of a graduated scale.

The method employed to turn an electrical into a mechanical force forms the classification of electrical instruments. In the earliest patterns such as the moving-magnet types, the electrical force was used in the form of a magnetic field which turned a magnet from its position of rest.

In the moving-iron pattern a piece of iron is magnetized by the passage of a current through a coil and is then either attracted towards the centre of the coil, as in the "single-iron" type, or repelled from an iron strip fixed axially inside the coil in what is called the "repulsion" or "double-iron" type (Figs. 1 and 2).

In the moving-coil system the current to be measured passes round a coil situated in a powerful field obtained from a permanent magnet. The current turns the coil into an electromagnet which reacts with the permanent-magnet field to produce a turning effect (Fig. 3).

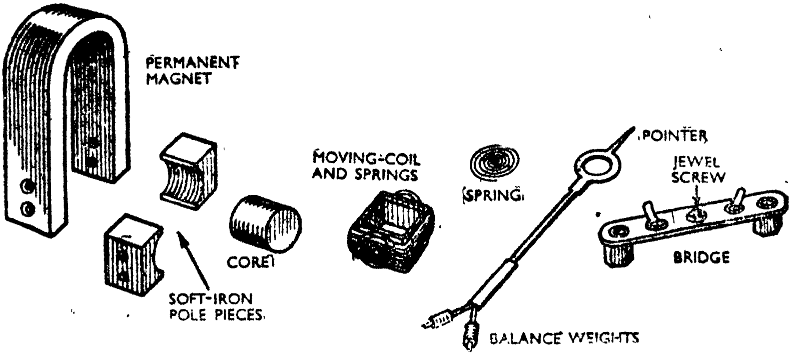
In the "dynamometer" or "electro-dynamic" pattern, the permanent magnet of the moving-coil system is replaced by an electromagnet so that two magnetic forces are produced which, between them, cause the rotation of the coil.

The induction pattern comprises an electromagnet system and a conducting disk. Eddy currents set up in the disk by the alternating magnetic fields, due to the measuring current, create a magnetic field which reacts with the originating field and so give rise to motion of the disk.

From the above it is seen that all the simple types of electrical measuring device, other than the electrostatic type, rely on a magnetic force which is produced by the current flow to be measured.

Electrostatic Voltmeter

The electrostatic voltmeter comprises a "variable condenser" assembly, familiar to radio men (Fig. 4), having the rotor assembly delicately balanced and pivoted. Electrostatic attraction, set up by connecting the voltage to be measured between the fixed and



COMPONENT PARTS OF A MOVING-COIL INSTRUMENT

Fig. 3. The operation of a moving-coil instrument depends upon the interaction between a permanent magnet and a coil carrying the current to be measured.

moving plates, causes the moving plates to enmesh with the fixed, the amount of movement being balanced, as before, by a spring.

One simple instrument once widely used, now almost neglected, is the hot-wire ammeter. The current to be measured passes through a thin wire fixed between two supports. The heating of the wire by the current causes it to lengthen and sag. The sag is taken up by a spring connected to the centre of the wire by a thread which also passes over a pulley. In taking up the sag, the pulley is rotated and a pointer attached to it indicates the value of current (Fig. 5).

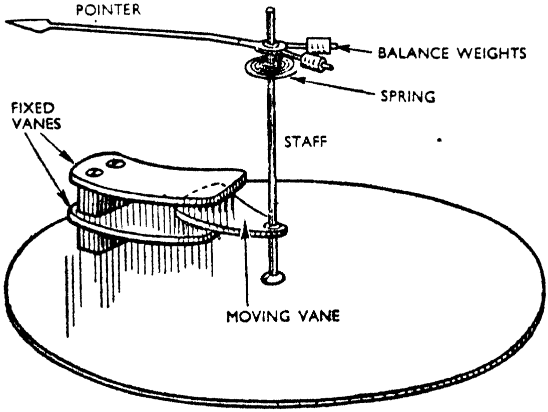


Fig. 4. Electrostatic voltmeters employ the familiar variable condenser principle. The voltage to be measured causes fixed and moving vanes to enmesh.

Classification

It is necessary, then, to classify instruments by their principle of operation and not by their electrical function, inasmuch as every simple and compound instrument listed above may be employed as a voltmeter, and all, except the electrostatic pattern, may be used as an ammeter.

Voltmeters are employed to measure the potential difference in a circuit and must be constructed to withstand the pressure in the circuit, except in the case of EHT systems, where it is usual to employ an isolating step-down transformer, so that the voltage applied

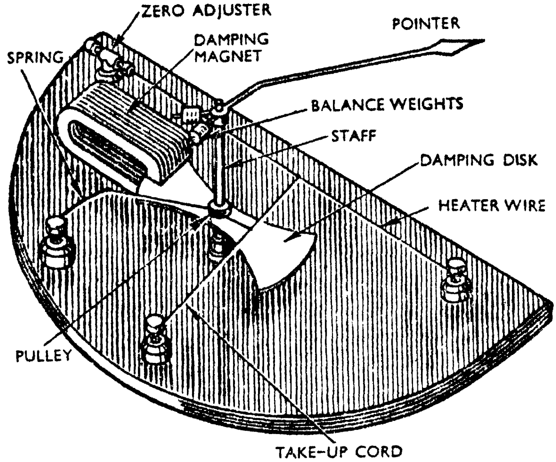
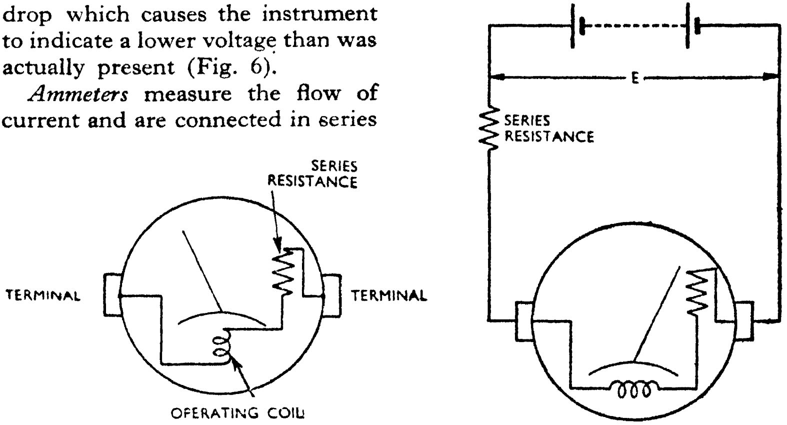


Fig. 5. Not so widely used as formerly, the hot-wire ammeter functions by the heating effect caused by an electric current in a thin wire.

to the instrument is small, of the order of 100 V, and the EHT stress is carried by the interwinding insulation of the transformer.

Voltmeters must be made to operate with a small current drain so that the power they consume shall be small. This is of importance in circuits of high resistance where the current required by the voltmeter, flowing through the resistance, sets up a volt drop which causes the instrument to indicate a lower voltage than was actually present (Fig. 6).

Ammeters measure the flow of current and are connected in series between the power source and the load. They should, therefore, have a very small resistance, and this is of particular importance in high-current, low-voltage circuits such as are employed for electro-plating.



VOLTMETERS MEASURE POTENTIAL DIFFERENCE

Fig. 6. (Left) Voltmeter circuit. (Right) Voltmeter in a circuit of high resistance. It must operate with low current so that power consumed in resistance is small.

When the current to be measured is greater than can conveniently be passed through the instrument, a proportion only is taken, the remainder being diverted through a *shunt* (Fig. 7) on D.C., or a current transformer on A.C.

Wattmeters in D.C. circuits must provide an indication that is proportional to $E \times I$, where E is the

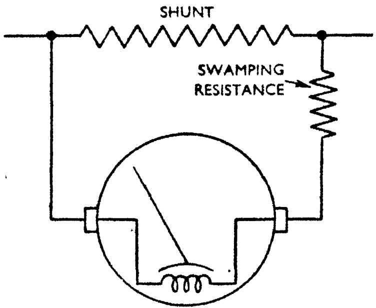


Fig. 7. Diagram showing how an ammeter with shunt is connected between the power source and the load. The swamping resistance should be more than three times that of the coil of the ammeter.

pressure and I is the current flowing in the circuit.

When connected to alternating-current circuits, the wattmeter is required to indicate, not $E \times I$, but $E \times I \cos \theta$, where θ is the phase angle by which the current leads or lags the applied voltage (Fig. 8).

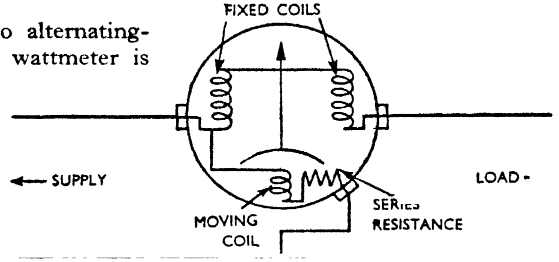


Fig. 8. D.C. or single-phase A.C. dynamometer wattmeter.

Although the wattmeter takes account of both voltage and current, its construction permits it only to indicate power. The separate components E and I cannot be measured separately with the one set of connections.

For the measurement of D.C. power or A.C. power in single-phase or three-phase balanced-load systems, a single movement is sufficient. For unbalanced-load conditions, however, the three-phase system requires a two- or three-movement indicator, depending upon whether three- or four-wire distribution is employed. The multi-movement instrument can be coupled to a single pointer which then indicates the sum total of the power in the separate phases (Fig. 9).

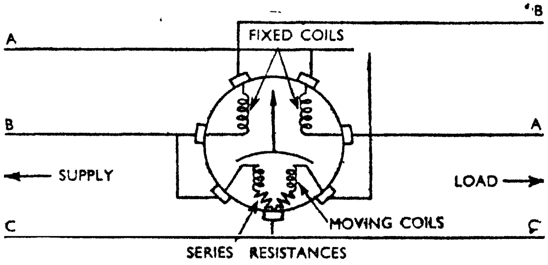


Fig. 9. Illustrating the connections of a three-phase unbalanced-load wattmeter (three-wire system).

Frequency meters are required to indicate the true frequency of the alternating supply to which they are connected irrespective of the voltage. These and power factor meters, which indicate the value of cos θ, again regardless of the circuit voltage, are special types which are described later.

Ohmmeters are subdivided as "voltmeter ohmmeters," which employ a standard moving-coil movement, and "true ohmmeters," which have a double-coil movement and give indications proportional to E/I. Both types require a voltage source which may be a primary or a secondary cell, the supply mains or, for insulation testing, a hand-driven high-voltage generator.

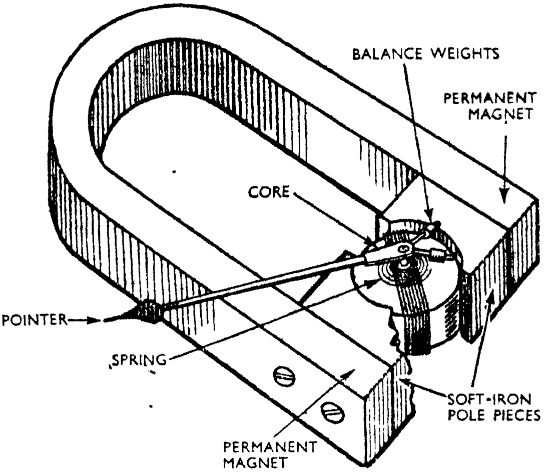


Fig. 10. Construction of a moving-coil instrument for general-purpose use, with the bridge removed.

In all the simple instruments to be described, other than the true ohmmeter, the mode of operation is to balance an electrical force, termed the "operating torque," against a spring; or, in the case of the older pattern, moving-iron types, against a weight. The spring or weight provides the "restoring torque" and the movement comes to rest when these torques are equal.

Since the operating torque of all instruments is a very small quantity, varying from 1 gramme centimetre (gr. cm.) in a lusty moving-coil movement down to ·01 gr. cm. in a low-volt-range electrostatic pattern, frictional losses must be kept to a minimum, otherwise the instrument will fail to find the true point of equilibrium.

It is clear that as the balance point is approached, the two torques tend to cancel out and the nett force acting on the movement approaches zero. Hence, any friction causes the movement to "stick," that is, come to rest away from the true equilibrium position.

Minimizing Friction

To reduce friction, the movement turns on hardened steel pivots which are mounted in cupped jewels, usually sapphires or rubies. The pivots have a radius at their bearing surface of the order of ·001 in., so that for a movement weighing 5 grammes the pressure on the jewel is of the order of 2 tons per sq. in. It will be seen that, since the moving parts must have weight, the movement is an oscillating system like the hair-spring and balance wheel of a watch and, in the absence of friction and windage, it would never come to rest.

Damping Force

To bring it to rest quickly, a further force must be introduced. This is termed the "damping force," since it tends to "damp out" the oscillations of movement and pointer. The damping force should be proportional to the rotational speed of the movement, so that as the movement comes to rest, the damping force diminishes to zero and has no effect on the final position.

Next, it is necessary that a pivoted instrument be counterbalanced so that it may operate in any plane. Examination of Fig. 10 shows that the moving-coil movement comprises a coil on its former carrying the pivots and a long pointer. In the absence of the balance weights, shown on the side of the coil opposite to the pointer; the movement would be "pointer heavy" and would be inaccurate when used in any plane other than that in which it was calibrated. When accurately balanced, however, the deflection will be independent of any position whatsoever of the instrument.

Temperature Compensation

A further source of possible inaccuracy is the change in ambient temperature. Consider the voltmeter of Fig. 6. The instrument is a current-measuring device which is scaled in voltage on the assumption that the voltmeter resistance has a constant value.

Now the temperature coefficient of copper is + ·4 per cent per deg. C., and this would cause the instrument to read 4 per cent low if the ambient temperature were 10 deg. above that at which the voltmeter was calibrated (if the resistance were made of copper wire). Hence, all the resistance other than the winding of the movement is made of material having a low temperature coefficient. Eureka, Constantan and Nichrome wires are used.

For the measurement of large currents a shunt is employed to by-pass a known proportion of the main flow (Fig. 7). Since widely differing currents will be passing through shunt and instrument and, on occasions, the two units may be in different places, the same temperature will not apply to both. The ammeter is made into a low-range voltmeter, having a full-scale deflection of the order of 75 mV. Circuit is partly copper and partly low-temperature coefficient material in the ratio of 1 to 3 or more. The shunt is then made of low-temperature coefficient material.

The overall accuracy of an instrument depends primarily on the type of movement employed. British Standard Specification 89 lays down the requirement for a first-grade instrument of each type.

For moving-iron or moving-coil voltmeters inaccuracy must not exceed 1 per cent of the deflection for any deflection from half-scale to full scale, and 1 per cent of a half-scale deflection for any deflection less than half scale. For electrostatic voltmeters, the figure is 2 per cent and for rectifier and thermo-couple types 3 per cent.

Even these permissible tolerances can lead to large errors in reading towards the zero end of the scale. Thus, when reading at one-tenth of full scale the permissible error is ± 5 per cent of the actual reading, whilst at one-twentieth of full scale the error is ± 10 per cent of the reading. Where a high degree of accuracy is required it is essential that the circuits be arranged so that the instrument indicates between mid and full scale.

Moving-iron Accuracy

Another point to be emphasized is the accuracy of the moving-iron types. It will be seen from the above that, contrary to popular ideas, the moving-iron types have the same intrinsic accuracy as the moving-coil pattern, and that for measurement of A.C. voltage and current at low frequencies, where there is sufficient power in the circuit to supply them, the modern

TABLE I

Type	*Functions*	*Suitable for use on*	*Power consumption Watts E = Full-scale voltage I = Full-scale current*	*Frequency limit on A.C.*	*Accuracy for B.S.I. expressed as a percentage of readings from full scale to half scale*	*Remarks*
Moving iron	Ammeter	A.C. and D.C.	·5 — 4 VA	Normal types power frequencies only. Special types up to 2 kc/s	2	Robust and accurate. Large power consumption
	Voltmeter	A.C. and D.C.	5 — 15 VA		1	
Moving coil	Ammeter	D.C. only	$I \times \cdot 075$	—	1	Robust and accurate. Small power consumption
	Voltmeter	D.C. only	$E \times \cdot 005$ down to $E \times \cdot 00005$		1	
Electrostatic	Voltmeter only	A.C. and D.C.	Negligible. Capacitance current only. Capacity of order of 10–50 $\mu\mu F$ for voltmeter of 3000 to 500 V respectively	Set by circuit conditions and constructional details. Of the order of 5 mc/s	2	Fragile in low-volt ranges (less than 500 V)
Dynamometer Air-cored	Ammeter	A.C. and D.C.	2 to 5	Up to 1 kc or higher, say, 5 kc with special design	2	Accurate, may be used as a transfer instrument from D.C. to A.C. Large power consumption
	Voltmeter	A.C. and D.C.	$E \times \cdot 05$ to $E \times \cdot 1$		[illegible]	
	Wattmeter	A.C. and D.C.	Current coil, 2 to 5 Voltage coil, $E \times \cdot 05$ to $E \times \cdot 1$		2½	
Dynamometer Iron-cored	Wattmeter	A.C. and D.C.	$3 + E \times \cdot 1$	40–60 c.p.s.	2½	Subject to frequency errors
Induction	Ammeter	A.C. only	4 to 10	Only suitable for power frequency 40–60 c.p.s.	2	Robust. Long scale. Large power-consumption
	Voltmeter	A.C. only	$E \times \cdot 05$ to $E \times \cdot 1$		1	
	Wattmeter	A.C. only	$2 + E \times \cdot 1$		2½	
Thermo-junction moving coil	Ammeter	A.C. or D.C.	Vacuum couple ·01 Open couple ·1	5–50 mc/s	3	Small overload capacity.
	Voltmeter	A.C. or D.C.	$E \times \cdot 005$ to $E \times \cdot 01$		3	Small overload capacity. Sluggish
Rectifier-operated moving coil	Ammeter	A.C. only	For I up to ·05 amp., watts $= I$. For larger currents a transformer may be used.	With careful design, 50 kc/s.	3	Low consumption. Subject to waveform errors
	Voltmeter	A.C. only	$E \times \cdot 05$ down to $E \times \cdot 0001$	Normal pattern, 5 to 10 kc/s	3	
Valve voltmeter	Voltmeter	A.C. or D.C.	Up to $\dfrac{E^2}{5 \times 10^6}$		Not listed	

patterns are far more suitable measuring devices than any other type. This statement takes into account the higher accuracy of the dynamometer types, which is only achieved by a larger power consumption and with a less robust movement.

Table I shows the major characteristics of the various types of instruments and the purposes to which they are most suited.

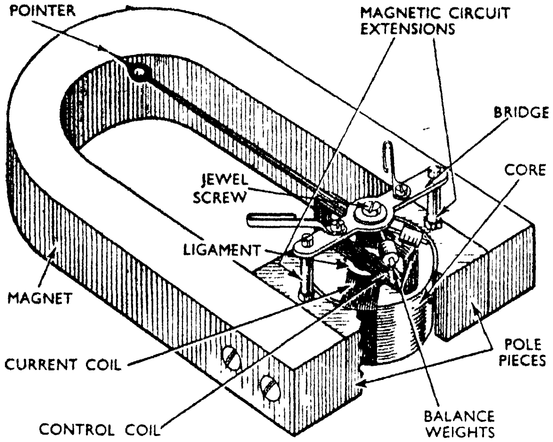


Fig. 12. Special type of moving-coil instrument is the true ohmmeter. Note fine ligaments that replace springs.

Moving-coil Principle

The construction of a typical moving-coil indicator can be seen from Figs. 10 and 11. A permanent magnet has a pair of pole-pieces which are arranged to have a cylindrical gap. In the centre of the gap is fitted the core, a smaller cylinder of magnetic material. An annular air-space is thus provided, having a width equal to the difference in the radii of the two cylinders. In this annular air-space is a radial magnetic field of approximately equal strength at all points.

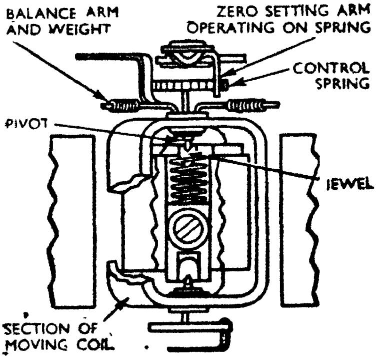


Fig. 11. Sectional sketch of a typical moving-coil instrument, revealing all the essential details of its construction.

In this annular space, a coil is fitted with its axis in line with the centre of the core and having either internal pivots moving in jewels fitted in the core (Fig. 11) or external pivots located in jewels fitted to a bridge (Fig. 10).

Two hairsprings of phosphor-bronze, cadmium copper, or other alloy are employed for the dual purpose of providing the control torque and the current-carrying connectors to the moving coil.

Current Flow

When current passes round the coil, a magnetic field is set up which reacts with the permanent field to move the coil. When the direction of current flow is reversed, the field due to the current is reversed and the direction of movement of the coil is reversed. Hence, the moving-coil indicator will not respond to alternating currents. It can be used only in D.C. circuits.

Since the coil is moving in a field of constant strength its movement is directly proportional to the current flowing and, as a result, the scale is evenly divided from zero up to full scale.

Damping is obtained by the use of a continuous metal coil former which acts as an eddy current brake, but where this provides too much damping, and, therefore, a sluggish movement, a sawcut may be made in the former. When there is space to spare on the moving coil the provision of a number of short-circuited turns gives a fine control of damping and, therefore, of speed of indication.

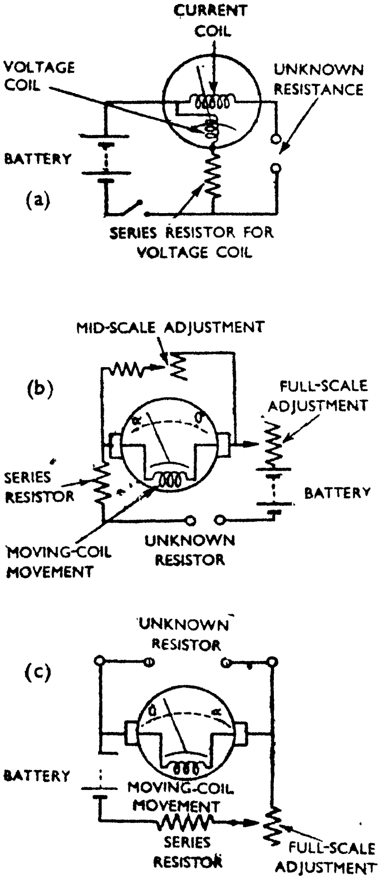


Fig. 13. Three ohmmeter circuits. (a) showing a true ohmmeter; (b) a voltmeter ohmmeter series circuit; at (c) is a voltmeter ohmmeter shunt circuit.

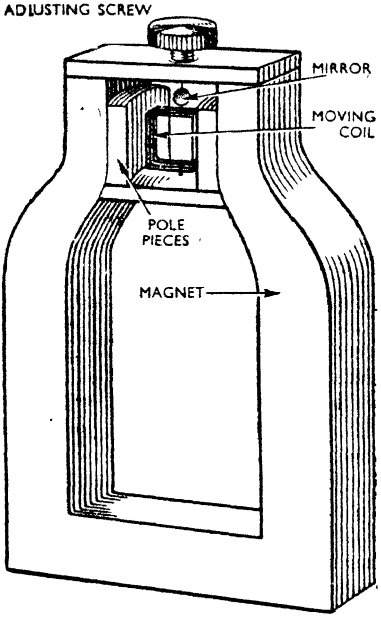


Fig. 14. Simplified illustration of a moving-coil galvanometer with the coil core removed for purposes of clarity.

The moving-coil indicator is extremely sensitive and normal pivoted types employing the latest pattern of powerful Alni and Alnico magnets give full-scale deflections with as little as ·02 of an ampere turn. In terms of watts, this means a power consumption of the order of 2 μW.

The type of winding employed on the coil depends on the full-scale voltage and current required.

For ammeters it is usual to have full-scale deflection with 5 mA or more and a volt drop of some 20 mV. This coil can then be connected to a shunt having 75 mV drop at full scale by way of a temperature compensating resistance or swamp (Fig. 7). This ammeter coil would have some twenty turns and a resistance of about 4 ohms.

For a super-sensitive voltmeter or galvanometer the coil would be wound with up to 1000 turns of very fine wire giving full-scale deflection with 50 μA or less.

It is clear that the full-scale deflection for a given instrument depends upon the permanent-magnet strength, the number of ampere turns on the coil and the strength of springs. Where sensitive instruments are concerned the first two are made as large as possible and the highest sensitivity is obtained by weakening the control springs. This leads to a less satisfactory instrument and, generally speaking, input powers of less than 10 μW are only obtained at the expense of robustness, which is a salient feature of the moving-coil indicator.

To sum up, the moving-coil meter is robust, has large working forces and an evenly divided scale. In its simple form it can measure direct current only.

True Ohmmeter

A special type of moving-coil instrument is the true ohmmeter (Fig. 12). This instrument has two coils and the springs are replaced by fine ligaments which lead the current to the coils without exerting appreciable control torque. The main coil carries the current to be measured, whilst the control coil carries a current which is proportional to the applied voltage (Fig. 13). The indication of such an instrument will be proportional to $\frac{E}{I}$; that is, to R, irrespective of the voltage applied to the circuit.

The current in the control coil must produce a torque similar to that obtained from a spring. That means that it must be small when the current in the main coil is small, and increase as the main coil current increases. Since the ampere turns are approximately constant, the coil must move in a graduated field produced by specially shaped pole pieces. Fig. 13 shows three ohmmeter circuits. Fig. 14 illustrates a moving-coil galvanometer.

Moving-iron Indicator

The moving-iron indicator comprises a coil having few turns of thick wire when it is required to measure current, and many turns of fine wire when it is to be used as a voltmeter. This coil must provide from 150 to 400 ampere-turns, depending upon the efficiency of the movement.

The moving system may be a single iron which is pulled into the coil by the magnetic field set up by the current in the coil (Fig. 1); alternatively, it may be a long strip which is repelled by a similar strip fixed along the axis of the coil. The latter is termed a double-iron or repulsion pattern (Fig. 2).

Damping cannot be conveniently carried out in the simple fashion employed in the moving-coil indicator, as any attempt to introduce a permanent magnet near the moving-iron system leads to distorted scale shapes and instability.

For this reason damping is usually obtained by an aluminium piston or paddle which is attached

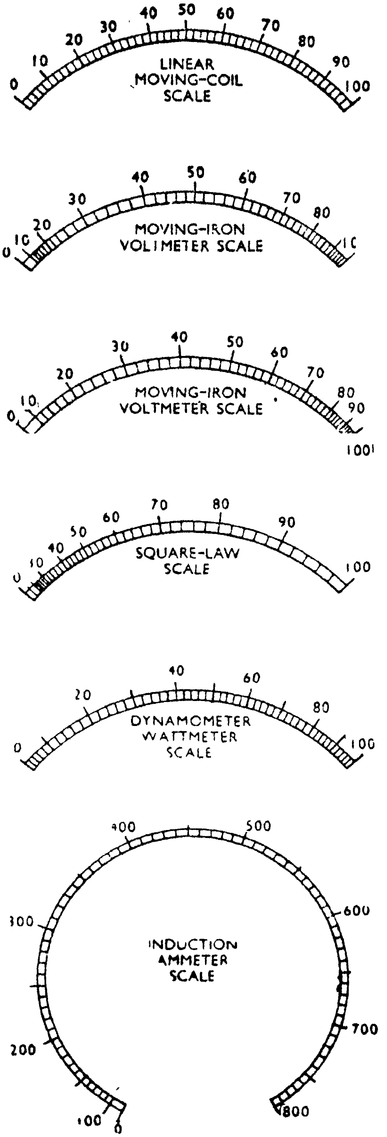


Fig. 15. In the linear scale of a moving-coil instrument, the readings are equally spaced through the whole range of the pointer's movement. In other cases, there is a closing up towards either or both of the ends and sometimes this is an advantage.

to the moving system and which moves in a tube or box (Fig. 1). To obtain effective damping the clearance between the edges of the piston, or paddle, and the sides of the tube, or box, must be kept to a minimum so that the rate of leakage of air past the damper is small.

The moving iron is magnetized by the flux set up by the measuring current; and so in both attraction and repulsion patterns the degree of magnetization of the iron and the field strength in which it moves are proportional to the ampere turns on the coil. Hence the torque is proportional to the square of the current.

When connected to alternating-current circuits, both the field and the magnetization of the iron change in each half cycle, so the nett effect, attraction or repulsion, persists throughout each cycle. The moving-iron instrument can, therefore, be employed for D.C. and for low-frequency A.C. measurement.

R.M.S. Values

The fact that the deflection is proportional to the square of current or voltage implies that when connected to A.C. the moving-iron ammeter or voltmeter indicates R.M.S. values.

In a simple pattern, the scale would be square law (Fig. 15), but modern instruments have specially shaped irons to give much nearer to a linear response. This shaping does not in any way affect the instrument's basic principle of square-law response and, therefore, does not affect its accuracy as an A.C. indicator.

The highest frequency at which a moving-iron instrument can be employed is set by the rise of impedance due to the inductance

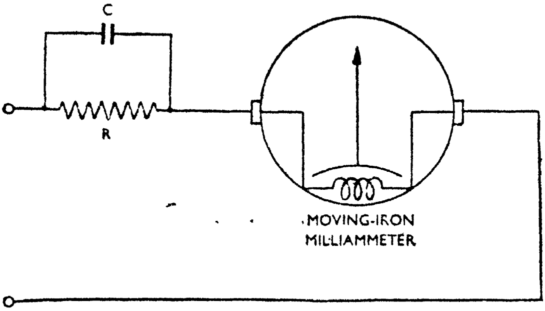


Fig. 16. Compensating device to extend the frequency range of a moving-iron voltmeter. Milliammeter, 0-100 mA; R, 1200 ohms; C, ·01mF. Compensation up to 2 kc/s (1 per cent error); 5 kc/s (5 per cent error).

of the coil. This results in an excessive volt drop across the coil when employed as an ammeter and a reduction of the voltage readings in the case of voltmeters. To offset the latter, a condenser may be connected across the voltmeter resistance (Fig. 16), and the useful frequency range can then be extended to a few thousand c.p.s.

This form of frequency compensation is most effective when the inductance of the coil is small, i.e. the number of turns small, and since the ampere-turns required by a particular movement are fixed, a larger current must be drawn.

The iron employed is usually a nickel iron alloy having an extremely small hysteresis loss. This is of special importance when used in D.C. circuits where excessive hysteresis causes the meter to read low when moving up scale, and high when moving from top scale to take up a lower setting. The flux density in the iron is generally kept low so that the peaks of A.C. do not carry the magnetization of the iron towards saturation.

Moving-iron ammeters and voltmeters are the most convenient instruments for measuring low-frequency A.C. and voltage when there is sufficient power available in the circuit to operate them.

Dynamometer

The electro-dynamic or dynamometer principle is similar to that of the D.C. motor. A moving coil (armature) moves in the field produced by the current to be measured. The movement has two springs which serve to exert the control torque and to feed the current in and out of the moving coil (Fig. 17).

The magnetic circuit may be all air, the usual case; alternatively, it may be part iron and part air. The former arrangement gives rise to a uniform field between the field coils so that, for a narrow moving coil, the deflection will be proportional to Φ_1, $\Phi_2 \sin \alpha$, where α is the effective angle between the two fluxes Φ_1, Φ_2. Thus its behaviour is

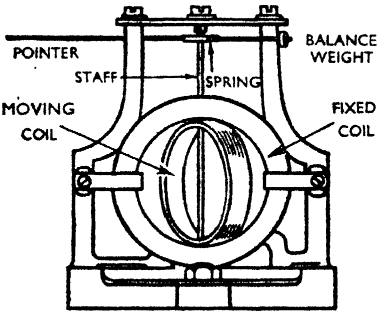


Fig. 17. Electro-dynamic or dynamometer principle is similar to that of a D.C. motor. Above is the dynamometer instrument construction in detail.

similar to that of a single coil on the armature of a D.C. motor.

It is usual to arrange that sin α is unity at mid-scale so that the decrease of torque only becomes serious at the extreme ends of the scale.

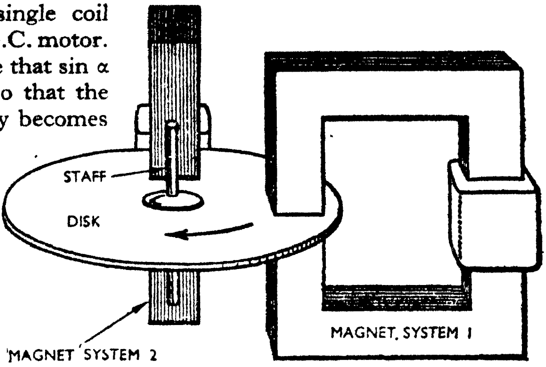


Fig. 18. Principle of induction instruments. Two magnets are fed with current, one in phase and the other lagging 90 deg. behind the applied voltage. Rotating field is produced, which results in rotation of disk.

The dynamometer instrument may be employed as an ammeter, having its fixed and moving coils in series or parallel; as a voltmeter, in which case the coils are connected in series; or as a wattmeter, when it is usual to pass the current to be measured through the fixed coils, whilst the moving coil is wound with many turns of fine wire and connected by way of a series resistance across the supply.

In the case of the wattmeter used on A.C., the readings are not proportional to Φ_1, Φ_2 sin α unless the currents producing the two fluxes are in phase.

Where there is a phase difference (θ) between them, the readings are proportional to Φ_1, Φ_2 cos θ sin α, because the two fluxes do not reach their maxima at the same instant. Thus the dynamometer wattmeter indicates power in watts on D.C., and true watts, that is, $E \times I \cos 0$, in A.C. circuits.

The dynamometer ammeter is sometimes used as a transfer instrument for the precise measurement of A.C. potentials by means of a potentiometer, since it can be calibrated on D.C., where far higher accuracies can be achieved, and subsequently used for A.C. measurements.

The air-cored dynamometer wattmeter has a scale evenly divided at about mid-point, but becoming cramped at each end, where sin α is decreasing rapidly.

The voltmeter and ammeter normally have a square law scale, but by arranging the zero close to the point where $\alpha = 90$ deg. a scale length of nearly 90 deg. can be obtained with the diminution of sin α operating against the square law of the instrument response, thereby giving a more linear scale. The use of short field coils, or the field distortion obtained when an iron core is introduced, both help to extend the length of scale where α is approx. 90 deg., thus giving rise to a more evenly divided scale on a wattmeter.

The introduction of iron, however, although reducing the total power consumed by the instrument, does introduce other sources of error, particularly with variations of frequency, so that for precision measurement the air-cored instrument is to be preferred.

The induction principle, similar to that employed in the induction

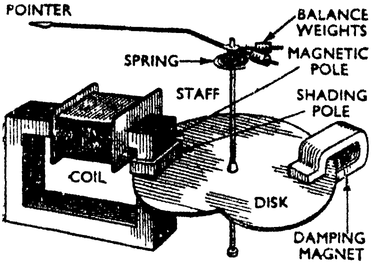


Fig. 19. Showing position of shading pole, causing a phase displacement.

motor, is applied to A.C. instruments for measuring voltage, current and power. It is also used for integrating meters for measuring watt-hours or kilowatt-hours.

Fig. 18 shows two electromagnets with a slot cut in their iron circuits. In these slots an aluminium disk is free to rotate against the torque of a control spring. A staff with pointer is attached and the movement is usually designed to have a deflection of about 300 deg.

In our example the two magnets are fed, one with current in phase and one with current lagging 90 deg. behind the applied voltage. A rotating field is thus produced and the reaction of the main field with the field caused by the eddy current flow in the disk results in rotation of the disk.

The necessary phase displacement can be obtained with a single electromagnet by means of a copper ring, or shading pole, fitted over one pole-face (Fig. 19). This acts as a short-circuited secondary turn and gives rise to a phase displacement between the main flux and the flux generated by the current flowing in the short-circuited turn.

The phase angle so obtained is less than 90 deg., due to the resistance of the magnet winding, the inductance of the short-circuited turn and the iron losses of the system, and this gives rise to a lower efficiency than that of the two-magnet design.

Proportional Torque

The torque is proportional to Φ_1, $\Phi_2 \sin \alpha$, where α is the phase angle between the two fluxes Φ_1 and Φ_2. Where these are arranged to be exactly at 90 deg. by construction, aided by refined adjustment, the two fluxes can be produced from a current and a voltage source, and if a further phase difference θ is introduced between these two sources, by reason of the conditions

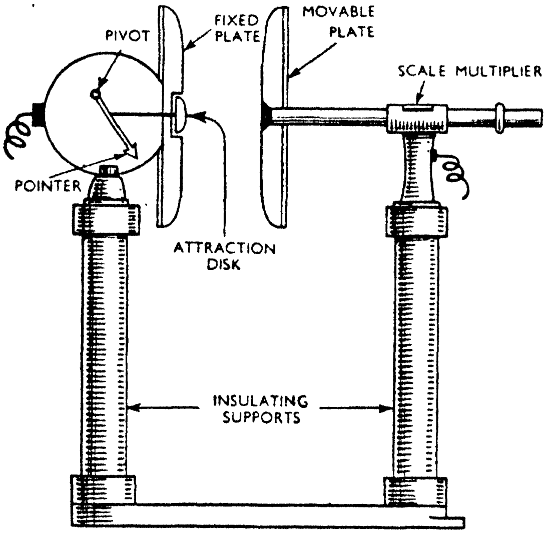


Fig. 20. Electrostatic voltmeter for 25 kV and above.

in the current circuit, the effective phase angle between the two fluxes is now $90 + \theta$, and the torque will be proportional to $\Phi_1, \Phi_2 \sin 90 + \theta = \Phi_1, \Phi_2 \cos \theta$.

In other words, by making the fluxes proportional to current and voltage respectively, and arranging that when fed by current in phase with the voltage these fluxes are exactly 90 deg. out of phase with each other, the system indicates A.C. watts.

Electrostatic Voltmeter

The electrostatic voltmeter (Fig. 20) employs the attractive force of an electrostatic field to produce the operating torque.

The movement comprises one or more condenser vanes, made of thin, ribbed aluminium foil fixed to a staff carrying the pointer and damping device.

A spring serves for control torque and to apply the voltage to the moving vane (Fig. 4).

Damping is applied either by a small tube or box similar to that used in moving-iron types (Fig. 2). Alternatively, eddy current damping is provided by an aluminium disk mounted on the staff moving in a strong field derived from a permanent magnet.

Details of Movement

The fixed portion of the condenser comprises aluminium vanes, one more than the number of moving vanes, so placed that the moving vanes are just beginning to mesh when the pointer is at zero.

The application of a voltage between the terminals, which are connected to the fixed and moving vanes respectively, causes the moving vanes to become more fully enmeshed, due to the electrostatic attraction between opposite electric charges.

Since there is an attractive force between both sets of plates acting upon the other, the indication will be proportional to the square of the applied voltage, and in alternating-voltage circuits the instrument will read R.M.S. values of the applied voltage.

The scale will be square law and only readable down to one-fifth of a full-scale deflection (Fig. 15).

A simple consideration will show that the torque of an electrostatic voltmeter is small as compared with a moving iron or other types. From the primary (e.s.u.) units it is seen that one electrostatic unit is the equivalent of 300 V, and that one magnetic unit is equal to 10 ampere-turns.

Increasing Torque

Whereas it is a simple matter to increase the number of ampere-turns in a moving-iron type, and this increase does not affect the weight of the moving parts, there is no similar method of increasing the torque of an electrostatic type.

Such increase is only possible by (*a*) reducing the clearances between the plates, an inadmissible course where high voltages are concerned, or (*b*) increasing the number of plates. This latter course increases the weight of the moving system.

For industrial purposes, electrostatic voltmeters are usually restricted to high-voltage work. Instruments having a full-scale deflection with less than 500 V are so delicate as to be more suitable for laboratory than industrial use.

The electrostatic voltmeter may be employed at high frequencies, so long as its capacitance, which varies with deflection, does not interfere with the operation of the circuit to which it is connected; and provided also that the insulation between the terminals and plates has a low enough loss factor to prevent overheating.

Thermo-junction M.C. Meters

Certain pairs of dissimilar metals exhibit a voltage when their junction is heated. This effect is employed in the thermo-junction moving-coil indicator, a current being employed to heat the junction of two metals, usually copper and constantan or nickel and nickel-chrome, the resulting voltage being applied to a normal moving-coil indicator.

Since the current to be measured can pass straight across the junction as opposed to the coiled path through all the magnetic devices, the thermo-junction instrument can be used for high-frequency alternating currents where the impedance and iron losses of the moving-iron types and the shunt capacitance of the rectifier-operated moving coil make these types unsuitable.

Commercial types are usually quoted as being suitable for current measurements up to 5 megacycles; but in practice a good design will be satisfactory up to 40 or 50.

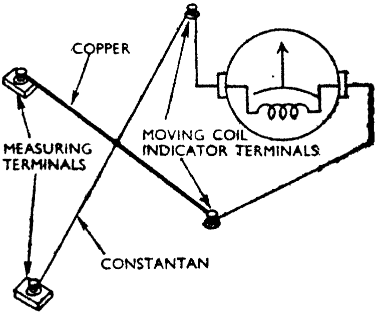


Fig. 21. In the thermo-junction moving-coil instrument, the current to be measured passes through and heats the junction between the dissimilar metals. This generates a voltage which operates the moving-coil indicator.

The heater and junction may take the form of a pair of crossed wires as shown in Fig. 21. Alternatively, the heater may be insulated from the junction which it surrounds. Where currents of the order of one ampere or more are to be measured, the junction is usually mounted inside the instrument case, where the terminal blocks are employed to keep the cold end of the junction wires cool. For small currents it is usual to mount the couple in a vacuum so that the small change of temperature at the junction shall not be affected by differences of ambient temperature.

The voltage output of the copper constantan couple is about 1 mV per 25 deg. C., and the moving coil is usually made to give full-scale deflection with 8 to 12 mV. The upper figure implies a temperature of 300 deg. C. for full scale, and this will only permit an overload of 100 per cent without endangering the couple. It is clear that a twice times current overload would give rise to approximately four times the heating, thus bringing the temperature of the junction up to 800 deg. or 1200 deg.

Skin Effect

At very high frequencies the instrument will read high because the "skin effect," whereby the current tends to crowd into the surface of the conductor instead of spreading all through it, as it does at lower frequencies, makes the resistance (R) of the heater higher.

heat is generated by a given current and the thermal voltage is greater, giving rise to a larger deflection on the moving-coil indicator. A scale has been devised whereby different markings are employed for different frequencies, but so far it has only been adopted for a hot-wire ammeter of special design.

Although it is mainly used as an ammeter, the thermo-junction moving-coil indicator is sometimes fitted with a non-inductive resistor of spiralized graphite pattern, to enable it to read radio-frequency voltage. The limitations of the resistance restrict the upper frequency range of such a voltmeter to the order of 5 to 10 megacycles.

Rectifier Bridge

The rectifier-operated moving-coil indicator is used for measuring A.C. or voltage. The almost universal circuit is shown in Fig. 22 and is known as the rectifier bridge.

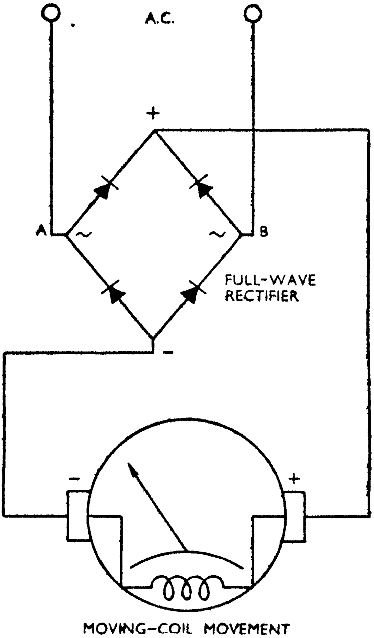


Fig. 22. Rectifier bridge circuit. This is in almost universal use in rectifier-operated moving-coil indicators.

From this it will be seen that both half-waves are rectified and passed through the meter in the same direction. During one half-cycle the path will be from *A* to +, through the meter, and then from − to *B*. On the next half-cycle the path is from *B* to +, through the meter, and then from − to *A*. Each half-cycle then carries up the pointer towards the peak value of the current flowing and allows it to fall back towards zero.

For very low frequencies, say five, or less, cycles per second, the pointer of a fast movement will actually trace out the individual half-cycles, but as the frequency increases, the movement is no longer able to respond to the rapid changes in instantaneous current values and so settles down to read the average value of each half-cycle.

This is unfortunate, since for most purposes it is not the average value but the root mean square value of voltage or current that is required. If the wave-form in question is truly sinusoidal, the instrument will indicate 89 per cent of the R.M.S. value and the scale can be marked off in R.M.S. values. This scaling, however, will only apply for sinusoidal wave-forms and the instrument will give inaccurate results when employed on distorted wave-shapes.

This disadvantage, however, is often outweighed by the fact that the rectifier-operated instruments are far more sensitive than moving-iron types and can, therefore, be employed in circuits of high resistance for the measurement of A.C. voltage, for the measurement of very small voltages, of the order of a few millivolts, and for the measurement of small A.C. currents from a few microamperes upwards.

In addition, they are satisfactory over a much wider frequency range than the moving-iron class, 10 kc/s being a common upper limit for commercial types, with 30 kc/s or higher being available in special instruments for special purposes.

Cause of Inaccuracies

There are two other causes of inaccuracy in rectifier instruments, temperature and low voltage characteristics. The former causes the instrument to read low with increase of temperature due to the lowering of the reverse resistance, the other causes an increase of resistance when small voltages are applied to the bridge, resulting in a cramped scale unless transformers (with their limitations to frequency range) are employed.

For these reasons the British Standard Specification lays down that the accuracy of a first-grade rectifier-operated moving-coil instrument shall be 3 per cent in place of the 1 per cent of the moving-coil type of instrument.

Valve Voltmeters

For the measurement of very-high-frequency alternating voltages no simple instrument is suitable and a *valve voltmeter* is employed. Also, for the measurement of small D.C. voltages where the circuit resistance is very large, a valve voltmeter with an amplifying stage supplies the most effective method.

Valve voltmeters employ a diode valve as a rectifying device to register the peak value of an alternating wave-form as shown in Fig. 23, or a triode valve as a rectifier and/or amplifier. Some types have a diode rectifier, followed by a triode amplifier, to give satisfactory readings on a robust moving-coil indicator.

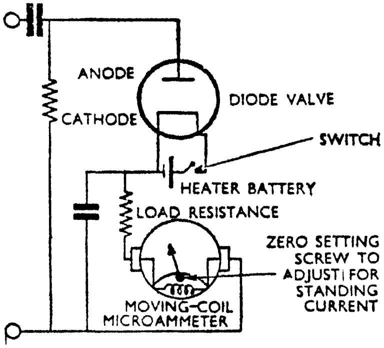


Fig. 23. Diode-pattern valve voltmeter, used for the measurement of very-high-frequency alternating voltages.

Direct-reading types have a moving-coil indicator calibrated in voltage. These must have a zero setting device to compensate for variations in the potentials supplied to the valve and the alterations of valve characteristics.

"Slide back" types employ a moving coil or electronic indicator. The indicator is set to a given mark or pattern, the potential to be measured is then connected, and a calibrated source of voltage is then applied in series opposition to the unknown potential. When the original indication is repeated the calibrated voltage is equal to the peak value of the unknown voltage. In this connection the system is similar to the potentiometer method of voltage measurement.

Lacking Stability

Due to a lack of stability, valve voltmeters are not suitable for measuring very small D.C. voltages, say, 50 millivolts or less. The upper frequency limit is set by the resonance point of the inductance of the leads with the valve's input capacity. By very careful design this limit can be made more than 100 mc/s.

Galvanometers

Galvanometers are sensitive instruments used for detecting the flow of small currents, or the presence of minute potentials. As a rule they are not scaled in electrical units.

The most common movement is the moving coil, although very high sensitivities are obtained with moving-magnet assemblies.

Instead of the pointer of normal instruments, the galvanometer often carries a small mirror on its movement (see Fig. 14). A light beam from a lamp is focused on to the mirror by a telescope and is reflected on to a ground-glass scale. This type is called a "mirror galvanometer" and, by reason of the reduction of the weight of the moving parts, has a faster movement than an equal pointer type.

The springs, pivots and jewels are usually replaced by a fine strip or wire suspension. This suspension serves to lead the current in and out of the moving coil, can be made to exercise a smaller control torque than a spring, and makes pivots and jewels unnecessary. This last removes the most frequent cause of "sticking" in normal instruments.

The sensitivity of mirror galvanometers is normally rated by the number of millimetres that the reflected light spot will travel along a scale at some stated distance from the movement, usually 1 metre. Clearly, it will be possible to double the sensitivity of a given movement by doubling the scale distance, although the mirror gives its sharpest image at the scale distance for which it has been ground.

Sensitivities as high as 10,000 mm. per microampere at 1 metre are achieved with delicate suspension mirror pattern galvanometers, whilst figures of 2000 mm. per microampere, or 25 mm. per microvolt, both at 1 metre, represent normal commercial sensitivities.

Although more sensitive than a pointer-type instrument, the mirror pattern suspension galvanometer is, generally, less robust than its pivoted counterpart.

Ballistic galvanometers have a heavy movement and a long periodic time. They are employed as coulomb meters to measure the total amount of current that flows in a short pulse and are scaled in ampere or milliampere seconds.

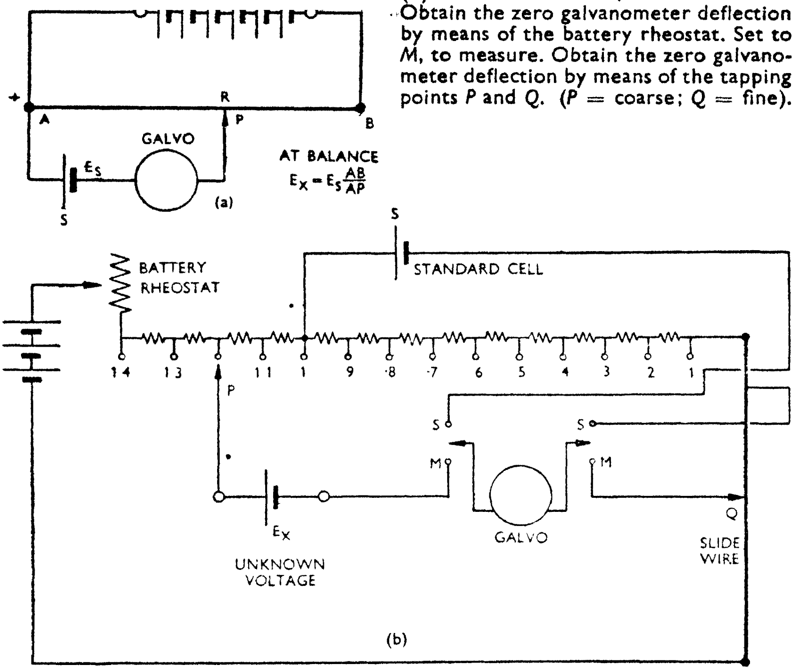
For detecting small alternating currents a vibration galvanometer is employed. This comprises a mirror suspension galvanometer which has a periodic time just equal to the frequency of the alternating supply to which it is connected. Under these conditions mechanical vibration of the movement is set up by very small alternating currents. The light reflected on to the scale is seen as a broad band due to persistence of vision. Null indication is given by the narrowing down of the band to a small line.

Potentiometers

Where a higher degree of accuracy than that shown in Table I is required in the measurement of voltage, a potentiometer is employed.

The simple potentiometer is indicated in Fig. 24, from which it

Fig. 24. (a) Potentiometer principle. (b) Set switch to S, to standardize. Obtain the zero galvanometer deflection by means of the battery rheostat. Set to *M*, to measure. Obtain the zero galvanometer deflection by means of the tapping points *P* and *Q*. (*P* = coarse; *Q* = fine).



is seen that if an unknown voltage E_x is connected as shown, there will be a fall of potential along the uniform calibrated slide wire *R*. By connecting a standard cell (E_s) via a galvanometer to a tapping point on the slide wire, a point will be found where the e.m.f. of the standard cell is equal and opposite to the potential developed across the length of slide wire from *A* to the tapping point *P*. At this point the galvanometer will read zero, and the unknown potential E_x is given by E_s multiplied by the ratio of the length of the slide wire to the length of the section *AP*.

As the value of E_s is known to four or more significant figures, a precise measurement of the two lengths of wire will enable E_x to be determined to an accuracy of ·1 per cent or better.

The above example explains the principle of the potentiometer. In practice, the standard cell is not employed for the balance, since any appreciable current taken from it, as for example by connecting it to an out-of-balance point, will destroy its accuracy.

Using Intermediate E.m.f.

For this reason an intermediate e.m.f. is used to pass a known current through the slide wire, which comprises both wound bobbins selected by a switch for coarse setting, together with the slide wire proper, which is used for the fine settings. A standard cell is used to check that the current flowing is the correct value and the unknown voltage is connected through the galvanometer to the E_x terminals.

As the system operates with a calibrated current flowing through known resistances, the resistance switches and the slide wire can be calibrated directly in voltage.

When the source of voltage E is larger than the unknown voltage E_x, no current will be drawn from the unknown voltage source. When the unknown voltage is the larger, however, a "volt box" or potential divider must be employed so that a small proportion only of E_x is connected to the potentiometer.

Since no current is drawn through the potentiometer from the E_x terminals, the actual voltage will be given by the indicated voltage on the potentiometer dials multiplied by the ratio of the potential divider resistance to that part of the resistance connected to the E_x terminals.

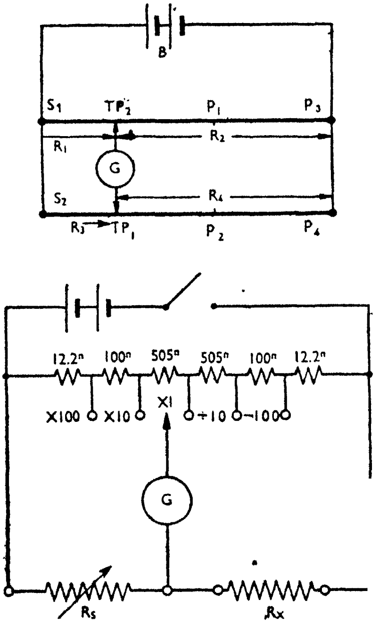


Fig. 25. (Top) Wheatstone bridge principle. (Bottom) Circuit for practical use.

There are a number of different circuit arrangements suitable for various purposes. The point of importance is the higher accuracy, as compared with a normal voltmeter, that can be achieved, and that without current drain, and also the facility for measuring extremely small e.m.f.'s.

Bridge Circuits

To obtain high accuracy in the measurement of resistance or reactance, the bridge circuits are widely employed. For resistances from about 1 ohm upwards the Wheatstone bridge is used; for lower values of resistance the Kelvin bridge is more suitable.

The simple example of a Wheatstone bridge is shown at Fig. 25, where two parallel slide wires of equal length, S_1 and S_2, are connected to a battery B. The galvanometer G will read zero whenever the tapping points TP_1 and TP_2 are at equal distances from one battery terminal. For example, if the galvanometer is tapped across p_1 and p_2, or p_3 and p_4, no current will flow through the galvanometer because the potentials of each pair indicated is the same.

Parallel Paths

From this it can be seen that if two parallel paths be provided across a voltage source, the potential of two intermediate points p_1 and p_2, one in each path, will be zero when the resistances R_1 and R_2 are in the same ratio as R_3 to

In its practical form, R_1 and R_2 become the ratio arms and can be set so that $\frac{R_2}{R_1}$ equals unity, $\frac{1}{10}$, $\frac{1}{100}$, 10 or 100.

R_4 is the unknown resistance and R_3 is a variable resistance of high accuracy, usually in the form of a "dial box," where four or five switches each control one decade, or a "plug box" in which plugs and sockets are used to select the required value of R_3. Balance is secured when $R_4 = R_3 \times \frac{R_2}{R_1}$, and by making the ratio arms multiples of 10 it is only necessary to multiply or divide the value of R_3, by moving the decimal point, in order to determine the value of R_4.

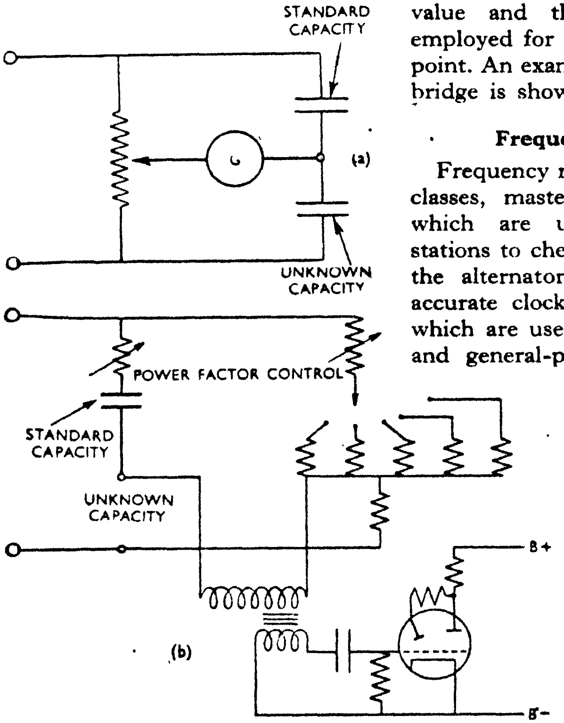


Fig. 26. (a) Simple A.C. bridge using two condensers, one of which is standard, and a vibration galvanometer G, or valve voltmeter. (b) Multi-range capacity bridge with "magic eye" balance indicator.

The accuracy of the Wheatstone bridge depends upon the accuracy of R_1, R_2 and R_3 and the sensitivity of the galvanometer. Accuracies of ·1 per cent are readily obtained when good-quality components are employed.

If R_3 of the Wheatstone bridge is replaced by a standard reactance X, and the battery replaced by a source of alternating voltage, an A.C. galvanometer or valve voltmeter will detect a balance when a reactance is connected in place of R_4.

Since a variable reactance is not usually convenient, X_s, the standard reactance, is normally a fixed value and the ratio arms are employed for defining the balance point. An example of a capacitance bridge is shown at Fig. 26.

Frequency Meters

Frequency meters fall into three classes, master frequency meters which are used at generating stations to check the frequency of the alternator output against an accurate clock, short-scale meters which are used in power circuits, and general-purpose type meters which are used for measuring speed and other mechanical purposes, in addition to electrical functions.

One form of master frequency meter takes the form of an invar pendulum clock having an accuracy better than ± one second per day. This drives a rotating scale, whilst a pointer, which is driven by a

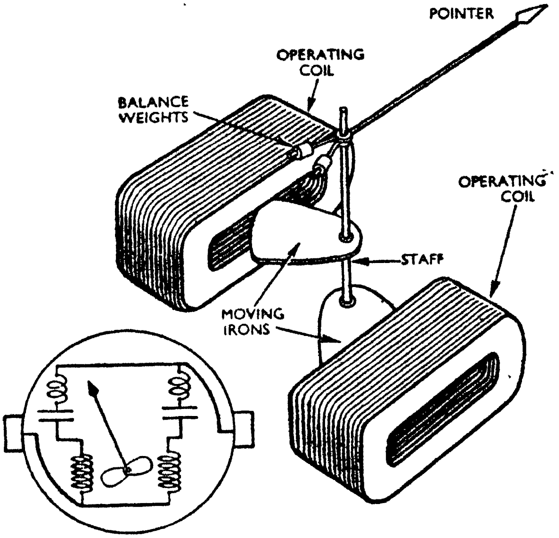


Fig. 27. Coleman moving-iron deflectional frequency meter. This pattern is suitable for short- or long-scale use. Note the two irons on one spindle.

synchronous motor, moves in front of it. The synchronous motor is connected to the alternator and keeps in step with it.

The gearing is arranged so that the master clock scale and its pointer turn at the same speed when the alternator is giving the correct frequency of output. The pointer moves forward with respect to the scale when the generated frequency is above normal and lags when the generated frequency is below the standard. The scale can be marked in "seconds gained" or "seconds lost." The instantaneous frequency can be seen from the relative speed of pointer and scale whilst the total time error is read from the scale.

Short-scale frequency meters have a small range of measurement on either side of the mean frequency of the supply to which they are connected—48 to 52, or even 49 to 51 c.p.s. are employed on 50 c.p.s. mains. They are usually of the deflectional type, being subdivided as moving iron, induction or dynamometer.

Coleman Type

The Coleman moving-iron deflectional frequency meter (Fig. 27) has two series-tuned circuits which are arranged to be at resonance at frequencies above and below the range of frequency to be measured. This pattern is, therefore, suitable for short- or long-scale use. In each series tuned circuit the operating coil of a moving-iron element is included and two moving irons are mounted on a common spindle.

When the impressed voltage has a frequency midway between the resonant frequency of the two circuits, the current flowing in each is equal and the pointer takes up a mid-position on the scale. As the frequency changes, one circuit takes more and the other less current so that one iron is attracted further into its coil, giving rise to a change of deflection. The other iron provides the control torque so that no springs are required and, since there are no moving conductors, no ligaments are necessary.

The difference of impedance of the two circuits to harmonic components is so small that practically equal amounts flow through, both making the indications practically independent of wave-form. Since the instrument is a ratio meter it is unaffected by voltage variations over a wide range.

The vibrating reed type (Fig. 28) has an electromagnet round which are mounted a number of tuned reeds. The magnet coil is connected across the supply and each reed is magnetized and attracted twice in every cycle of the applied A.C. The reed, having a natural period equal to twice the frequency of the applied current, will vibrate with a greater amplitude than the remainder.

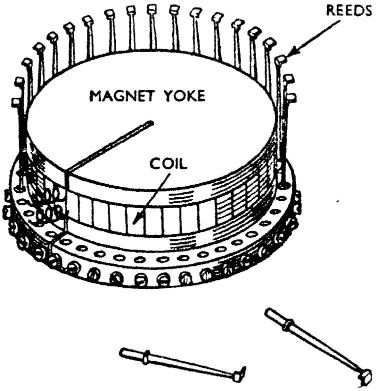


Fig. 28. Frequency of the applied A.C. is indicated by vibration of tuned reeds.

By arranging the reeds end on to the viewer, and turning over the front edge, so that it normally appears square, the increase of amplitude becomes apparent in the form of a thickening of the reed end which is assisted by persistence of vision. The scale markings are one-half of the natural frequency of the reeds, that is to say, the instrument indicates the frequency of the applied A.C.

If the instrument is polarized, either by D.C. or a permanent magnet, giving a field strength equal to that of the applied A.C., the reeds will only be attracted once per cycle, and the reed, having a natural period equal to the applied A.C., will vibrate. By this means a vibration-reed frequency meter can be given two ranges, one usually as scaled, and the second, the scaling multiplied by two, which is used when the polarization is applied.

The Weston pattern has two coils set at right angles and a moving iron which takes up a position depending upon the resultant flux in the system. One coil is made highly inductive, whilst the other is of low inductance. They are connected to a potential divider comprising resistance and inductance so that the circuit forms a "bridge" across the supply.

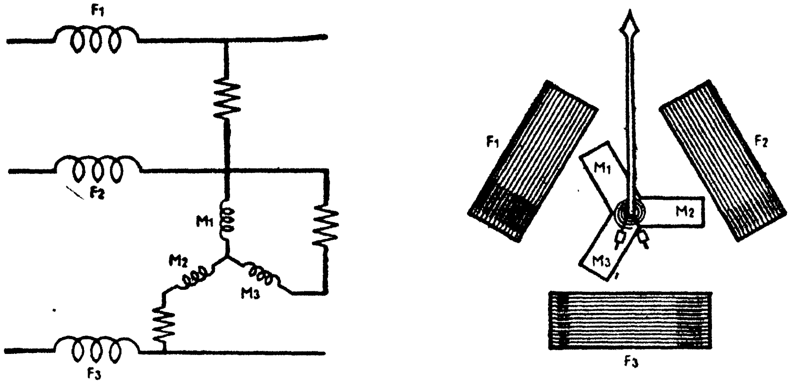
Clearly an increase of frequency causes an increase of inductive reactance and a larger current to flow through the lower reactive path. The behaviour is similar to the ohmmeter inasmuch as it is independent of applied voltage over a wide range and, of course, no control springs are required.

The induction pattern resembles a wattmeter, but again has no control spring. It is necessary to shape the disk for the same reasons that the magnetic field is distorted in the true ohmmeter, that is, to give stability of deflection under all conditions.

Power-factor Meters

Power-factor meters are required to indicate the phase relationship between the current and the applied voltage in a single or multi-phase circuit, irrespective of the value of current and voltage (Fig. 29).

The simplest pattern is similar to the dynamometer movement



THREE-PHASE POWER-FACTOR METER

Fig. 29. (Left) Theoretical diagram for a three-phase power-factor meter. (Right) shows the arrangement of the fixed (F_1, F_2, and F_3) and moving (M_1, M_2, and M_3) coils.

shown in Fig. 17. It has two moving coils set at right angles to each other, in place of the single coil seen in the diagram.

The two moving coils are fed from the pressure circuit, one through a resistance and the other through a choke or condenser. Fine ligaments are used to lead the current in and out of the coils instead of springs, so that they exert a negligible control torque. The current in the two coils will be in quadrature, one being in phase with the line volts, the other leading or lagging the line volts by approximately 90 deg.

Fixed Coils

The fixed coils are placed in series with the current path and so generate a flux that is in phase with the line current.

Consider, first, the case when the line current is in phase with the voltage. From the dynamometer equation we can see that there will be no torque generated by the moving coil carrying the current in quadrature with the voltage, so that in this instance the other moving coil, carrying current in phase, is drawn so that it stands at right angles to the main flux. The

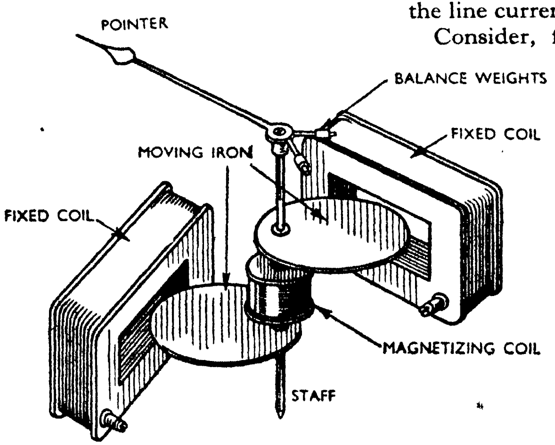


Fig. 30. Single-phase moving-iron power-factor meter. A vertical magnetic spindle passes through the current coil, which has an iron at each end.

pointer will then indicate 0 deg., the angle of lag, or more commonly its cosine, unity, which is the power factor in this case.

Similarly, if the current in the stator coils lags the voltage by 90 deg., the moving coil carrying the quadrature current will be attracted and the pointer will set itself at right angles to the previous indication, that is, at 90 deg., or power factor = 0.

Coil Attraction

Again, if the current in the stator coil leads the supply voltage, the coil carrying the quadrature current will be attracted, but this time in the reverse direction. The scale will be marked 90 — 0 — 90, or 0 — 1 — 0 power factor.

The indications at intermediate scale points are due to the resultant torques of the two moving coils and so are independent of applied voltage over a certain range. The ligaments, however, are liable to upset the accuracy, since they must exert a certain torque, however small, which will prevent the moving system from coming to rest in the true zero torque position.

Three-phase Pattern

The three-phase pattern is shown at Fig. 29, from which it will be seen that at any instant the "quadrature coil" of the single-phase pattern is replaced by the two coils each set at 120 deg. to the main coil, and that these functions change three times in each cycle. The principle of operation is the same as the single-phase model, but the construction is complicated by the extra moving coil and ligament.

Besides exercising a small torque, which leads to inaccuracies when the total current in the system is low, the ligaments prevent the movement from completing a full 360 deg. of rotation. To overcome this, modern designs of phase meter have a moving-iron system operated on by two coils placed so that their fluxes are at right angles.

Fig. 30 shows a single-phase pattern where a vertical magnetic spindle passes through the current coil and has two irons mounted at each end of the coil. The two voltage coils are mounted so that their axes are 90 deg. apart. They attract or repel the irons, depending upon the instantaneous polarity of the irons, which is controlled by the flux generated by the line current flowing through the centre coil.

Integrating Meters

Integrating meters are measuring instruments which indicate the sum total of current or power that passes, irrespective of the instantaneous values of such current or power. They count up either ampere-hours or kilowatt-hours and indicate on a set of dials; alternatively, they operate a cyclometer train.

A simpler pattern uses the electrolytic action of the passing current to alter the level of a liquid in a calibrated tube (Fig. 31).

Integrating meters are fitted in the premises of practically every consumer of electricity and serve to count the units of electricity consumed so that an appropriate charge may be made. On occasions they are combined with a coin-in-the-slot device to secure payment in advance for any current supplied.

Integrating meters are classed by function as ampere-hour meters or kilowatt-hour meters.

All modern meters are of the motor type, the induction pattern

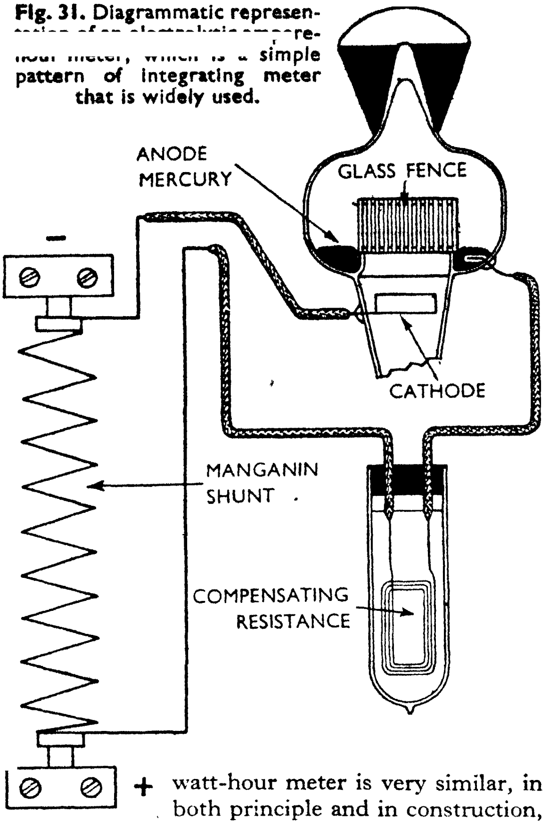


Fig. 31. Diagrammatic representation of an electrolytic ampere-hour meter, which is a simple pattern of integrating meter that is widely used.

being used for A.C. and the commutator type for D.C. The steady reduction in the total of consumers on D.C. supplies has brought about a restriction in the use of the other D.C. meters. These are (*a*) the mercury motor, in which a disk armature floats in mercury and so renders brushgear unnecessary; (*b*) the pendulum meter, which has magnetic control of two pendulums, one being accelerated and the other retarded by line current so that the difference in their speeds is proportional to current and a differential gear train connects to the dial mechanism, and (*c*) the electrolytic meter.

The pendulum meter can be used on A.C., but its greater cost as compared with the induction watt-meter restricts its use.

The types of integrating meter with their main characteristics are shown in Table II. This is to be found overleaf on page 294.

Operating Torque

The operating torque of the commutator ampere-hour meter is produced by the same means as in the moving-coil ammeter. The commutator watt-hour meter is basically similar to the dynamometer wattmeter, whilst the induction watt-hour meter is very similar, in both principle and in construction, to the induction wattmeter.

Whereas it is possible in the case of the indicating instrument to arrange a balance between the operating and control torques, the integrating meter must be capable of continuous movement.

Instead of the control and damping torques of the indicating types, a retarding force or "brake" is applied. If no such force were available the meter would speed up and the rate of counting would depend upon friction and windage. Clearly, any variation of these would lead to serious inaccuracies.

The brake represents so great a proportion of the total load on the motor that changes in friction, etc., have negligible effect.

TABLE II

Type	*Suitable for use on*	*Similar indicating instrument*	*Consumption (watts) where* I *= line current,* E *= line volts*	*Remarks*
Commutator ampere-hour	D.C.	Moving-coil ammeter	$1 \times I$	Simple. Difficulty in keeping brush friction and contact resistance to their original setting.
Commutator watt-hour	D.C. or A.C.	Dynamometer wattmeter	$7 + E \times {\cdot}015$	Used mostly for D.C.
Mercury meter ampere-hour	D.C.	—	${\cdot}25\ I$	No brushes.
Electrolytic	D.C.	—	${\cdot}5 - 1\ I$	No moving parts. When reset all previous records are obliterated.
Pendulum watt-hour meter	A.C. or D.C.	—	$5 + {\cdot}15\ E$	Expensive to produce. Accurate. Will record small currents without complicated compensating arrangements.
Induction watt-hour	A.C.	Induction wattmeter	$2 + {\cdot}01\ E$	Efficient and inexpensive.

The retarding torque must have a value that is proportional to the speed of the motor. It is usually produced by means of a conducting disk moving in the field of a permanent magnet.

Eddy Currents

The eddy currents set up in this disk as it rotates in the magnetic field produce magnetic flux which reacts with and opposes the originating flux.

The accuracy of the meter depends upon the constancy of these opposing forces. It is desirable that changes in ambient temperature should affect both to an equal degree. For this reason the brake magnet of the induction wattmeter operates on the same disk as the operating magnet system. Changes of resistance of the disk, caused by varying temperature, affect the eddy currents of the braking system and the induced currents of the driving system equally, and so the total error produced by the change is small. By comparison with the indicating meter, which has only to move a balanced pointer, the integrating meter has to do a lot of work. A larger power consumption is natural so that sufficient torque can be produced to turn the counting train or cyclometer.

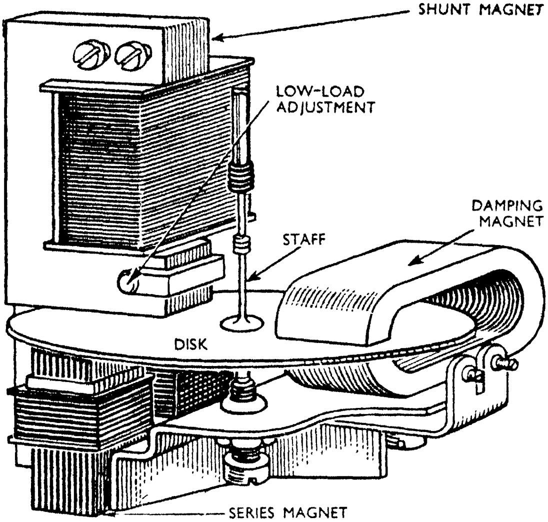


Fig. 32. Single-phase induction watt-hour meter, used extensively for the measurement of A.C. supply. In operation, it is similar to the induction wattmeter.

Torque

It is essential that sufficient torque is available even when the rate of flow of current is small. Otherwise the passage of a current just insufficient to start the meter might go unrecorded for a long, long time; a serious matter for the supplier of electrical energy.

To overcome this possibility a friction compensation or "low load adjustment" is fitted. It takes the form of some shunt device which provides a small torque, *almost* sufficient to overcome the frictional losses, even when no current is being drawn through the meter. (In the case of wattmeters it is essential to check so that the meter will not run on "no load current" even when the voltage is raised to something about 10 per cent above the normal figure.)

Standard Counting Train

Another point of difference between indicating instruments and integrating meters is that whereas the former can be hand calibrated and have a scale specially written, the latter must operate a standard counting train. For this reason it is necessary to make the motor speed variable to allow for the normal manufacturing tolerances.

Controlling Speed

On the commutator wattmeter and induction wattmeter types, the speed variation is controlled by the position of the brake magnet. It will be appreciated that the speed of the part of the disk under the pole face will be less as the pole face is moved in towards the centre of the disk. Hence the induced voltage will be less, the eddy currents smaller, and the braking torque will be reduced, so allowing the meter to run faster for a given load current.

The overall accuracy required of motor meters is set out in B.S.S.37. The meter must record to an accuracy of +2½ to −3½ per cent and be tested at 5 and 125 per cent of normal full load, in addition to a third test at some intermediate value.

For the measurement of A.C. supplies the induction watt-hour meter is almost universally employed (Fig. 32). It comprises an aluminium disk which is mounted with its spindle in a vertical plane, having a pivot and jewel at the lower end of the spindle. The spindle is coupled to the counting train by way of a worm or other means, and the disk is operated on by two magnetic fields.

Producing Magnetic Fields

These are produced by the current through a coil in series with the load and another, wound with fine wire, connected across the source of supply voltage. Electrical spacing of 90 deg. is obtained by making the shunt circuit highly inductive so that its flux lags the applied voltage. The braking torque is provided by a permanent magnet mounted in the instrument, as far from the operating magnetic system as possible.

Induction Watt-hour Meter

The principle of operation is exactly the same as that of the induction wattmeter previously described, where it was seen that the rotating field produced by two fluxes at right angles gave rise to a torque which was proportional to Φ_1, Φ_2 sin 90 deg., where Φ_1 and Φ_2 are the fluxes caused by the current and pressure coils, and the line current is in phase with the voltage. When the current is out of phase with the voltage in the load circuit by an angle θ, the fluxes will be separated not by 90 deg. but 90 deg. $+ \theta$. Sin $90 + \theta = \cos \theta$; therefore, the torque is proportional to $EI \cos \theta$, that is, to the power in the load circuit.

On three-phase circuits a single element meter, such as that described above, can only be employed when the phases are balanced, i.e. when the bulk of the load is represented by three-phase equipment such as induction motors and the like, and the single-phase load such as lighting is evenly distributed between the phases.

Where the load is unbalanced, it is necessary to use a three-element meter having either three magnetic systems mounted round a single disk or, alternatively, three separate motor units mounted on a common shaft, or operated independently.

Calibration

The adjustments provided for calibration purposes are the phase adjustment, usually in the form of a short-circuited turn fitted round the shunt magnet, which can be moved so as to embrace more or less of the flux and so alter the effective phase angle of the shunt flux ; the full-load adjustment, made by shifting the brake magnet towards the centre of the disk, to reduce the braking torque, and so increase the speed of the disk for a given power input.

Lastly, the compensating strip, which is a kind of extra "shaded pole," mounted near the shunt magnet so that it tends to produce a torque from the voltage winding alone, i.e. with no current in the series coil. Movement of this pole, which takes the form of a strip of copper, so that it is nearer the shunt pole face, increases the compensating or low load torque.

To conclude this chapter some reference may be made to the commutator types of ampere-hour and watt-hour meters.

The construction of the commutator ampere-hour meter is reminiscent of those simple toy motors comprising a permanent magnet and wound armature with a small three-or-more segment commutator.

Although the drum armature is used, the disk armature, having three or more flat coils contained in an aluminium capsule, is more widely employed. The connections from the coil are brought out to the commutator, whilst delicate brushes, exerting a very small pressure, serve to pass the current to and from the commutator segments. It is usual to fit a shunt so that the brushes only carry a small proportion of the total current to be measured.

The field is produced by a permanent magnet, which also sets up eddy currents in the aluminium capsule to create the braking torque.

The armature is fitted to a vertical spindle which drives counting train through suitable gearing.

The wattmeter is illustrated at Fig. 33 and the armature bears a resemblance to the moving section of the dynamometer wattmeter.

General Construction

The moving coils are wound with fine wire and connected to the voltage source through a large resistance. The fixed coils are connected in series with the load current for the smaller sizes, and across a shunt which by-passes a known fraction of the total current where the load current is too large to pass through the fixed coils direct.

The operating torque is proportional to the two fluxes, that is, to $E \times I$, so that the meter integrates watt-hours. A separate disk is fitted to the spindle with a permanent magnet arranged for eddy current braking. The friction-compensating or low-load adjustment comprises an adjustable coil placed near the fixed coils and connected by a large resistance to the voltage terminals. It produces a small field under no-load conditions and so assists the armature to start when only a small load current is flowing.

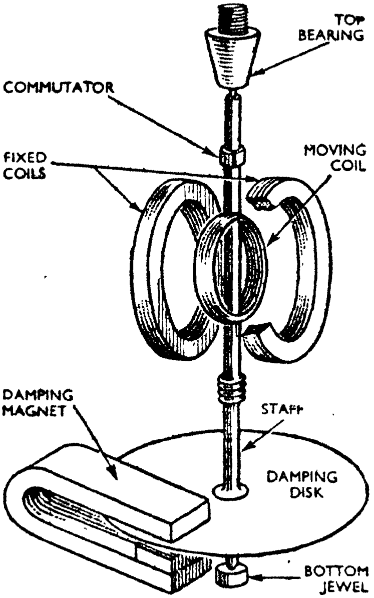


Fig. 33. Showing component parts of a commutator-pattern watt-hour meter.

The difference between the two types of meter is that the watt-hour meter measures the product of watts and time, whereas watt-hours can be obtained only from the readings of an ampere-hour meter if the value of the supply voltage is assumed or measured.

CHAPTER 13

DISTRIBUTION AND CONTROL OF ELECTRICITY

D.C. AND A.C. SUPPLIES. THREE-PHASE FOUR-WIRE AND THREE-PHASE THREE-WIRE SYSTEMS. EARTHING OF SYSTEMS. TRANSMISSION-DISTRIBUTION SCHEME. GRID SYSTEM. PYLONS AND POLES. INSULATORS. EARTH WIRES. HOUSE SERVICES. OVERHEAD AND UNDERGROUND SYSTEMS. JOINTING. SUB-STATIONS. SWITCHGEAR. CIRCUIT-BREAKERS. FUSEGEAR. RELAYS AND PROTECTIVE GEAR. PROTECTION FROM LIGHTNING. REMOTE CONTROL OF SWITCHGEAR.

CURRENT distributed by the mains may be either direct (D.C.) or alternating (A.C.). In the early days, when power stations were small and supplied limited areas in the immediate neighbourhood, D.C. was suitable. As supply areas expanded, the cables became longer and the increased resistance introduced serious losses of voltage and power.

One remedy in such a case is to reduce the resistance by using cables of larger cross-section. But copper is expensive and an economical limit is soon reached.

The only other solution is to generate at a higher voltage. For a given power, an increase of voltage permits a reduction of current—and it is the current which causes the voltage drop in cables. For example, by doubling the

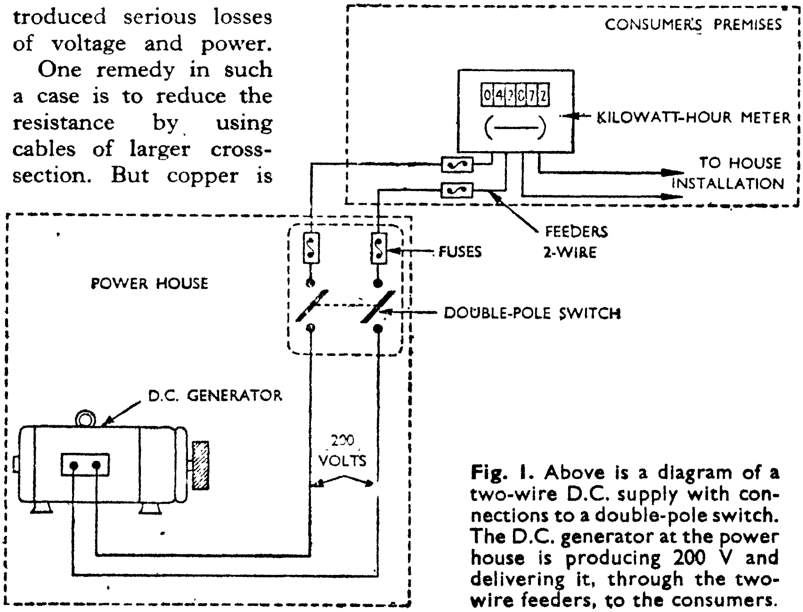


Fig. 1. Above is a diagram of a two-wire D.C. supply with connections to a double-pole switch. The D.C. generator at the power house is producing 200 V and delivering it, through the two-wire feeders, to the consumers.

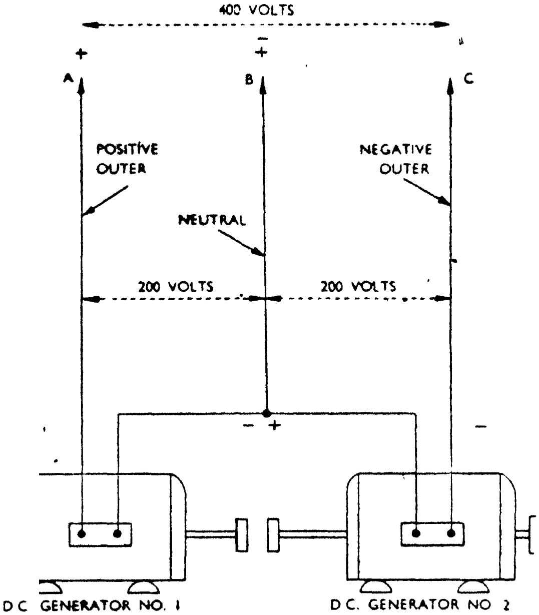


Fig. 2. How a three-wire 400/200-V D.C. supply is arranged. Two generators are connected in series and supply a 400-V system with a neutral "return" conductor, to provide two 200-V D.C. systems. Three feeders are taken from the points of supply, *A*, *B* and *C*.

voltage, twice as much power can be conveyed with the same current and the same voltage loss in the cable.

With the D.C. this remedy, like the first, can be applied only to a limited extent. D.C. cannot easily be transformed down in voltage and so the generation voltage must not exceed what is reasonably safe in the home of the consumer.

Now with A.C. the generation voltage can be high, and yet transformers can be used wherever necessary to step down to lower pressures. The current can be reduced to a minimum, thereby saving copper and ensuring low losses. This is why A.C. is now the standard supply in this country and why D.C., even though it has advantages for some power applications, is being ousted.

D.C. Systems

In describing the different methods employed for distributing current, a start will be made with D.C. systems, as they are still found in some places and also form a simple introduction to the slightly more complicated arrangements used with A.C.

A very simple D.C. supply circuit is indicated in Fig. 1. Direct current at 200 V is obtained from the generator and is delivered through the main cables (usually called " feeders ") to consumer.

Within limits it is possible to increase the range of a D.C. system by the adoption of a three-wire distribution method, as illustrated in Fig. 2. This method is in general use in this country where D.C. is still utilized. Two D.C. generators are connected in series, each providing current at 200 V. Three feeders are taken from the points of supply, *A*, *B* and *C*.

The potential difference between *AB* and *BC* is maintained at 200 V, while, of course, between *A* and *C* it is 400 V.

Although three feeders only are employed, and not four, they may be thought of as separate circuits, with feeder *B*, the "neutral," carrying the outward current of one circuit and the inward current of the other.

Although this neutral does the work of two feeders, it is not necessary for the cable to be twice the size of the other two. The greatest current which it will carry will not exceed that in either *A* or *C* and, under the best conditions, when the currents in the two circuits are equal, no current at all will flow through it (Fig. 3). Every effort is made, therefore, by the supply engineer, to provide a balance of current in the circuits.

Out-of-balance Current

Assuming 10 A flow through the neutral feeder in both directions simultaneously, the resultant in *C* is 10 − 10 A = 0.

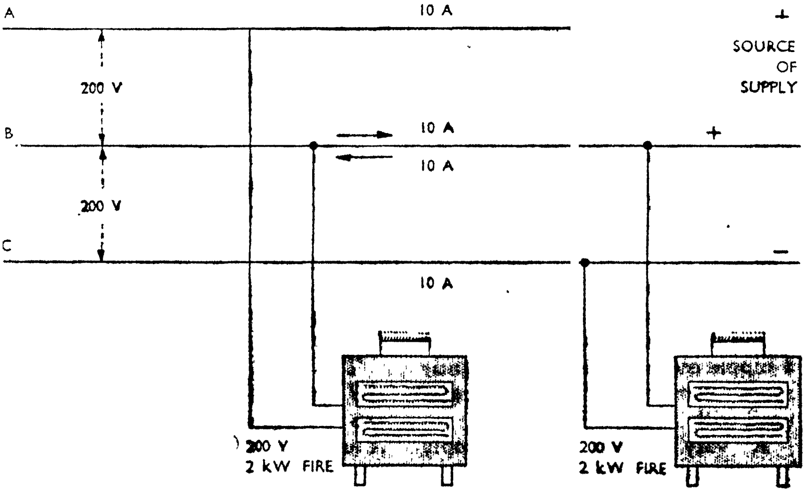
If a further load of 5 A were connected across *AB*, the current through feeder *A* would be 15 A and the current through the neutral would be 15 − 10 = 5 A. This is known as the out-of-balance current of the system.

There are various systems of A.C. supply: single-phase two-wire distribution, three-phase four-wire and three-phase three-wire.

A single-phase two-wire system is identical with that of the two-wire D.C. method, as illustrated in Fig. 1. It is rarely adopted for a complete distribution scheme, but is often utilized for extensions from three-phase systems to supply isolated premises.

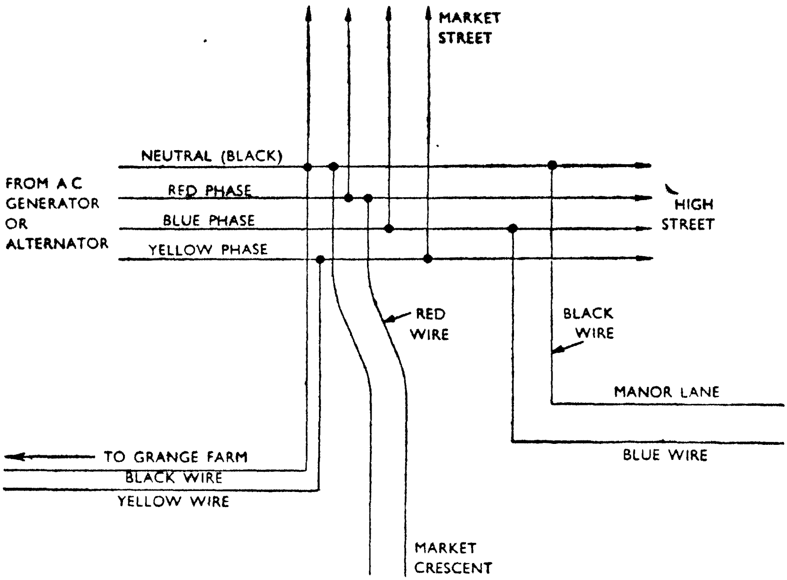
Three A.C. circuits may be combined and utilized either together as a "three-phase" supply, or independently as three single-phase systems, although in all cases the current is obtained from one A.C. generator having three interconnected windings.

For normal distribution work a three-phase four-wire network is adopted. For purposes of distinguishing one phase from another, each circuit is coloured. For



THREE-WIRE 400/200-V D.C. SUPPLY

Fig. 3. Theoretical diagram showing balanced current loads on the two 200-V circuits of Fig. 2, with zero current flowing through the neutral conductor.



THREE-PHASE FOUR-WIRE DISTRIBUTION

Fig. 4. Theoretical diagram of connections to distribution scheme enabling single-phase two-wire extensions to be made to less-populated streets and an isolated farm.

example, *A* phase is red, *B* phase blue, *C* phase yellow and the fourth wire, the neutral, is coloured black. These colours are not adopted by every supply undertaking but are the ones usually employed.

Fig. 4 gives a typical layout of a portion of a three-phase four-wire distribution scheme. It will be seen that all three phases supply the High Street and Market Street, while single-phase two-wire systems supply two small streets and an isolated farm. A balance of load is obtained as far as possible, although the loads are not shown in the diagram.

To provide a balance over the three phases, the consumers' individual installations are connected by the supply engineer to any of the three phases, depending upon the amount of load installed at the various premises. Fig. 5 illustrates how this is carried out. If the loads in the three houses are identical and are on at the same time, no current flows through the neutral in the same manner that no current flows through that conductor in the D.C. system illustrated in Fig. 3.

Balanced Loads

In Fig. 5 the loads connected to each of the phases *A*, *B* and *C* are not identical. The current supplying the mill is evenly distributed over the three phases and may be considered as balanced. No neutral wire has been provided, since it is not necessary.

The domestic load of 13 kW has been distributed as far as possible over the three phases: phases *A* and *B* supplying 5 kW each; phase *C* supplying 3 kW to house A. This difference in load will cause an out-of-balance current to flow through

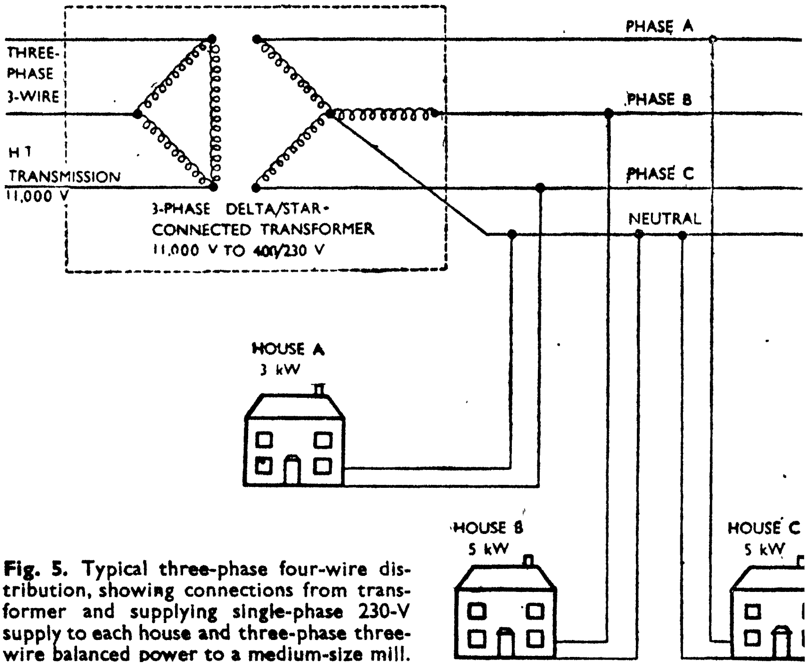

THREE-PHASE 3-WIRE H T TRANSMISSION 11,000 V
3-PHASE DELTA/STAR-CONNECTED TRANSFORMER 11,000 V TO 400/230 V
PHASE A
PHASE B
PHASE C
NEUTRAL
HOUSE A 3 kW
HOUSE B 5 kW
HOUSE C 5 kW

Fig. 5. Typical three-phase four-wire distribution, showing connections from transformer and supplying single-phase 230-V supply to each house and three-phase three-wire balanced power to a medium-size mill.

the neutral conductor. The supply engineer is not able to determine accurately what out-of-balance current will flow as this will vary from time to time, depending upon the varying requirements of each consumer in houses *A*, *B* and *C*. At one period house *B* may use a load amounting to 3 kW, while at another time he may, if necessary, utilize his maximum connected load of 5 kW.

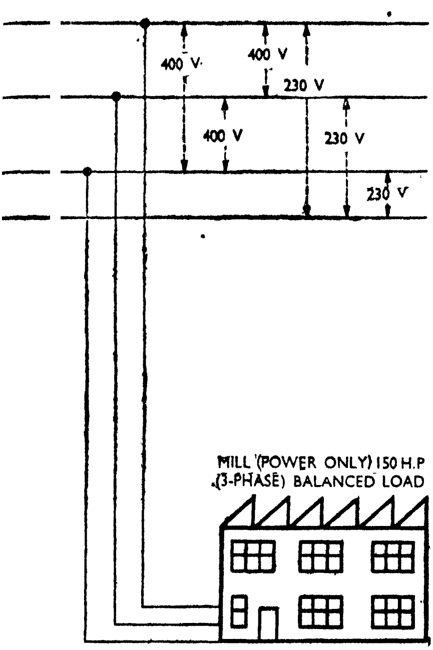
The load in kW as shown in Fig. 5 is termed the "paper load" and from this an experienced supply engineer is able to determine the size of cable and equipment required, depending upon the nature of this load, viz. whether lighting, space heating, water heating or cooking.

For example, where the load consists entirely of lighting and heating, it is highly probable that on a cold winter night the total load will be in use simultaneously; but should cooking and water heating load be installed instead of, or in addition to, heating, the actual maximum load will probably be lower than the paper load.

Line and Phase Voltages

The connections to the delta-star transformer in Fig. 5 are the normal ones where supply is transformed from high-tension (H.T.) distribution to the low-tension (L.T.) distribution network. The theory of such connections is more fully dealt with in Chapter 10.

Three-phase three-wire systems are used only for supplying balanced load where no neutral conductor is required to carry any out-of-balance current. Most common application



is to supply three-phase balanced power to electric motors as already suggested in Fig. 5.

For high-voltage transmission, the three-phase three-wire system is employed. Again, Fig. 5 shows a typical arrangement where the H.T. supply is delivered to the transformer by three feeders and three-phase four-wire output is provided to the L.T. system.

The standard three-phase three-wire transmission is illustrated in simple form in Fig. 6.

The line voltage of a system is the difference of potential between each phase. The standard in this country for L.T. supplies is 400 V, as shown in Fig. 6. On the H.T. side, 11,000 V is a standard line voltage.

Phase voltage is the difference of potential between any one phase and the neutral conductor, the standard in this country being 230 V. With three-phase four-wire systems the phase voltage is always equivalent to :

$$\frac{\text{Line voltage}}{\sqrt{3}} = \frac{400}{} = \frac{400}{}$$

The standard system is described as 400/230 V. With non-standard systems, when either the phase or the line voltage is known, the other can be obtained by applying the above formula.

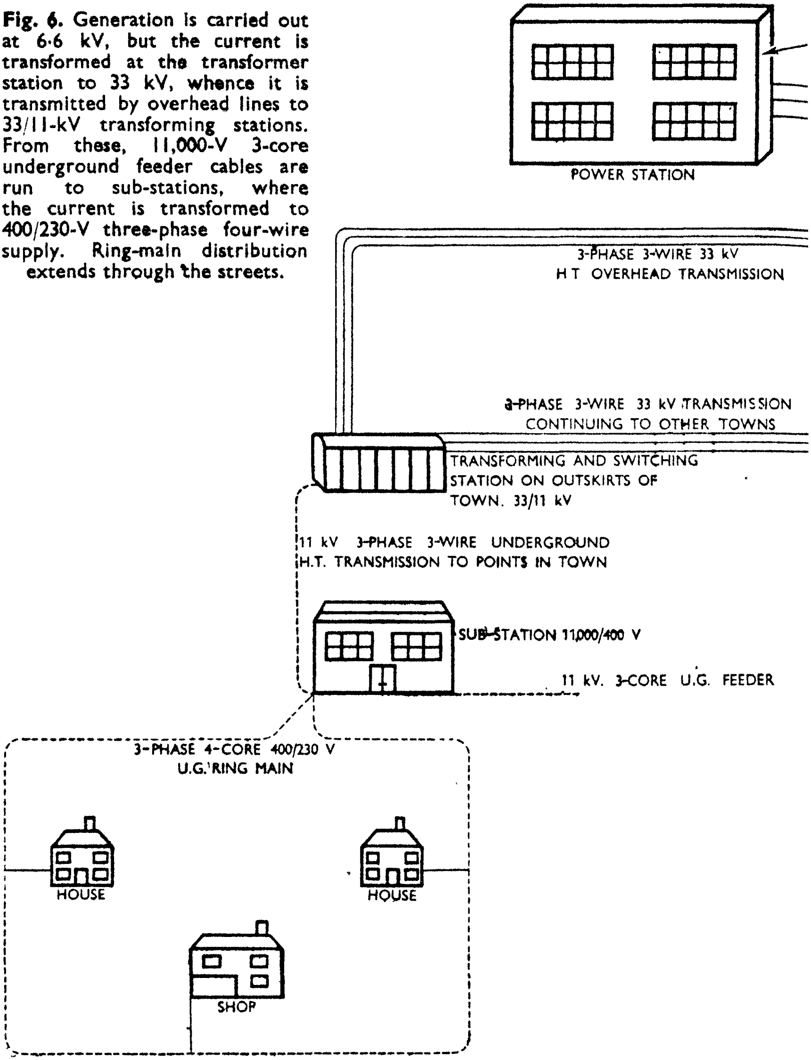
It is normal practice to earth the neutral at the star point of the secondary winding of the transformer. This ensures that no part of the system is more than 230 V above earth potential.

Testing Earth Circuit

The earth circuit can be tested as shown in Fig. 7. A lamp (230-V rating) is applied between connection *N* (neutral) and the earth, and the lamp should not light. If it does the system is at fault. As the difference of potential between *AB* and *BC* is 400 V, the leads should not be placed across them or the lamp will burn out. As a precaution, when trying to identify leads, two 230-V lamps may be connected in series. The lamps will glow only when applied between each phase and earth but will be bright when applied between phases.

Where current is to be transmitted over long distances, the voltage at the source (generator) is transformed to high pressure of 33 kV or, in some cases, 66 kV and even 132 kV.

Overhead distribution is normally employed and at a suitable point at each town or village the current is transformed down to 11 kV or 6·6 kV. H.T. feeders operating at these pressures are

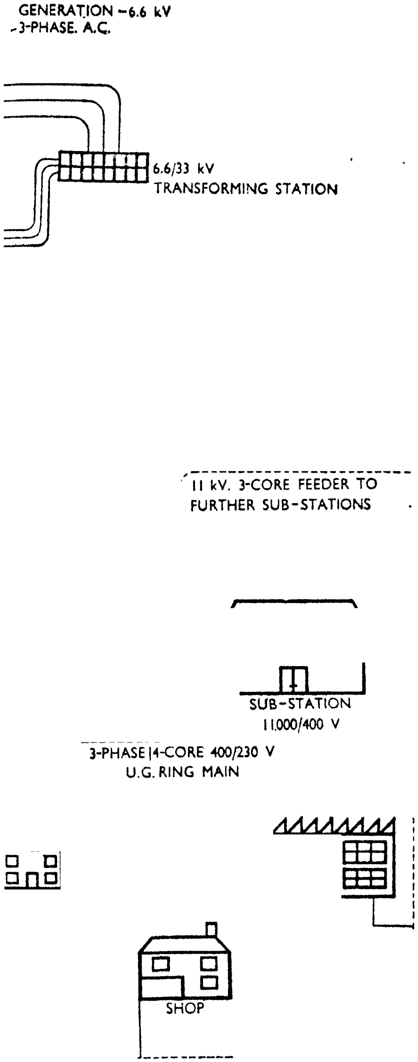


POWER STATION
3-PHASE 3-WIRE 33 kV
H T OVERHEAD TRANSMISSION
3-PHASE 3-WIRE 33 kV TRANSMISSION
CONTINUING TO OTHER TOWNS
TRANSFORMING AND SWITCHING
STATION ON OUTSKIRTS OF
TOWN. 33/11 kV
11 kV 3-PHASE 3-WIRE UNDERGROUND
H.T. TRANSMISSION TO POINTS IN TOWN
SUB-STATION 11,000/400 V
11 kV. 3-CORE U.G. FEEDER
3-PHASE 4-CORE 400/230 V
U.G. RING MAIN
HOUSE
HOUSE
SHOP

Fig. 6. Generation is carried out at 6·6 kV, but the current is transformed at the transformer station to 33 kV, whence it is transmitted by overhead lines to 33/11-kV transforming stations. From these, 11,000-V 3-core underground feeder cables are run to sub-stations, where the current is transformed to 400/230-V three-phase four-wire supply. Ring-main distribution extends through the streets.

then laid underground (overhead in rural areas) to various transformer stations or sub-stations, where, by using delta-star connected transformers, the four-wire L.T. supply is obtained.

Where possible, to eliminate interruption of supply, "ring" mains are employed as suggested in Fig. 8. In many instances the 11-kV transmission schemes form a "ring main" for the same reason. When faults occur the faulty section of cable is isolated and the supply restored with the exception of the faulty length which is later



renewed or repaired, as the case may be.

This form of layout also helps in keeping the pressure of supply within the limits imposed by the Electricity Supply Acts, which is ± 6 V at the consumer's premises. Where the ring main is extended, additional feeders may be provided. For example, referring to Fig. 8, additional feeders may be connected to points 4 and 8.

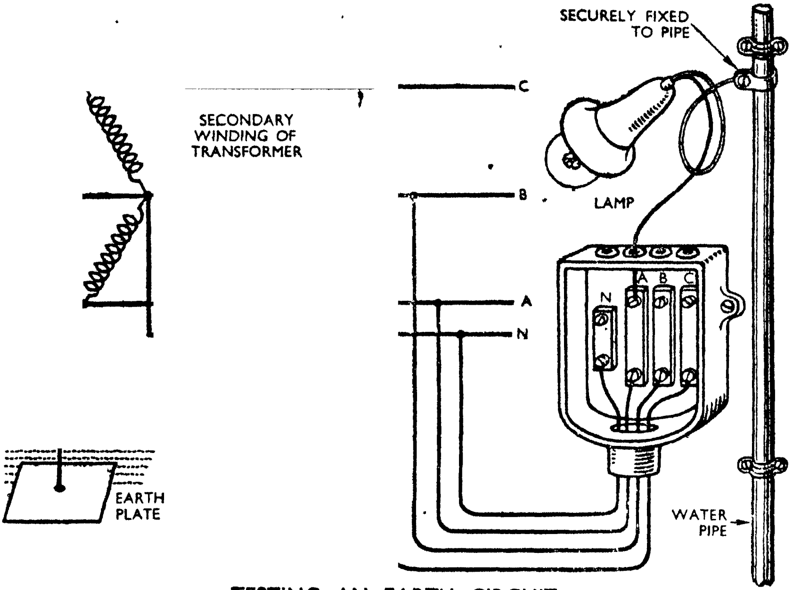
In industrial areas H.T. distribution is employed for extensions. The 11-kV or 6·6-kV feeders are extended down most of the streets, forming "ring" mains. Tappings are made adjacent to all or most consumers' premises. Transformer chambers are then provided on the actual premises. Voltage drop is negligible and consumers' appliances may be connected to the system practically without limit.

Grid Scheme

Following the passing of the Electricity Supply Act, 1926, which provided for the formation of the Central Electricity Board, the National Grid Scheme was constructed. This comprises several thousands of miles of extra-high-pressure (EHP) cables operating at 132 kV and mounted on steel latticed pylons.

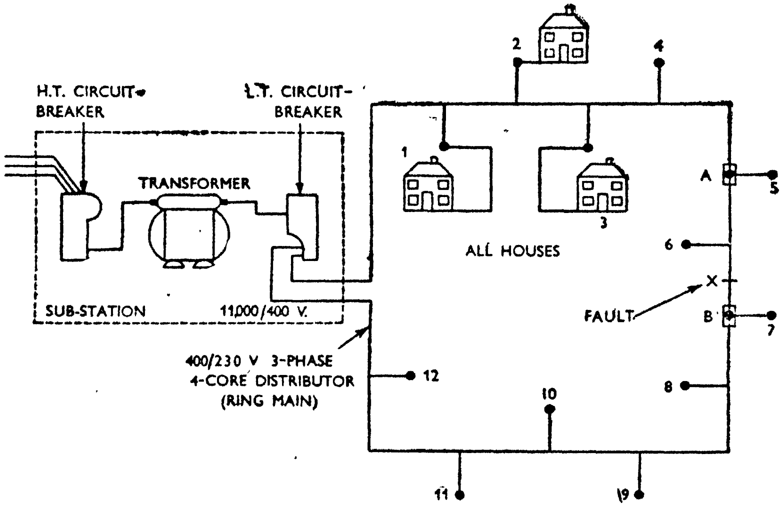
Fig. 9 shows a typical pylon for a single-circuit (three-wire) three-phase system, while Fig. 15c is a drawing of the standard type of string insulator. A fourth wire, known as the continuous earth wire, is fixed to the apex of each pylon. This cable normally carries no current but may carry earth fault current should such develop. A second function is that of a continuous lightning conductor, since it is fixed at the highest point of the system and affords protection from lightning strikes.

Sections of the Grid operate at a lower pressure of 33 kV. Although the pylons and cables are identical with those used on the higher voltage system, this secondary



TESTING AN EARTH CIRCUIT

Fig. 7. 230-V pilot lamp should give full brilliancy with one wire on "earthed" water-pipe and the other alternatively to connections *A*, *B* or *C* of the incoming supply cut-outs.



ADVANTAGE OF EMPLOYING A RING MAIN

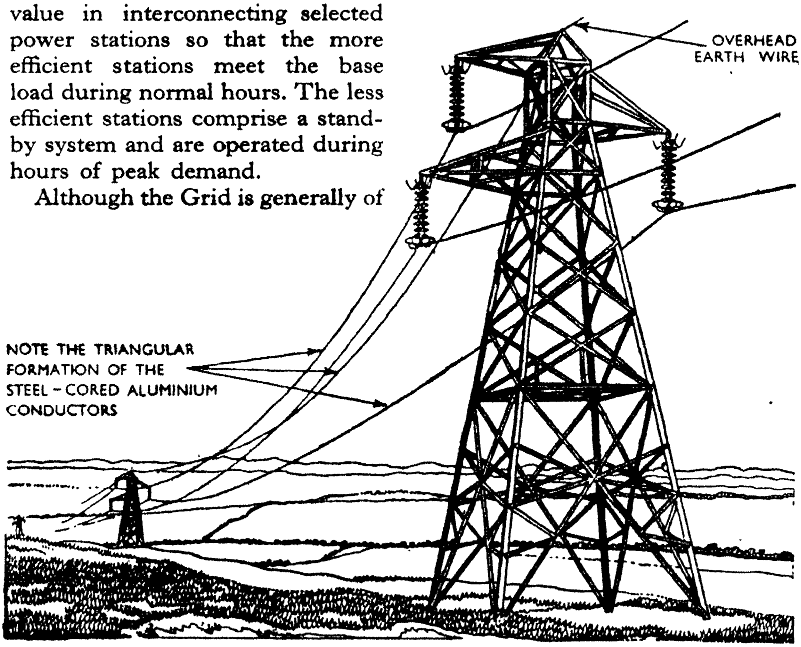
Fig. 8. If a fault occurs at point *X*, a portion of the distribution is cut out at points *A* and *B*. Only Consumer 6 is without supply, whereas six premises would be involved were supply to terminate at point 12 instead of returning to sub-station.

system is identified by observing the insulators, which comprise four units in a string instead of nine seen on the 132-kV sections.

Interconnecting Stations

Apart from making electricity available over the greater part of Britain, the Grid also has great value in interconnecting selected power stations so that the more efficient stations meet the base load during normal hours. The less efficient stations comprise a stand-by system and are operated during hours of peak demand.

Although the Grid is generally of overhead construction, some portions of it are underground, the most extensive section of this character being the network which interconnects the London power stations.


OVERHEAD EARTH WIRE
NOTE THE TRIANGULAR FORMATION OF THE STEEL-CORED ALUMINIUM CONDUCTORS

STEEL PYLON USED IN GRID SCHEME

Fig. 9. Illustrated is a steel-latticed pylon used in a 132,000-V EHP transmission scheme. Note the 9-tier suspension-type insulators which, with these pylons, are employed as standard on the British Grid system.

The necessity of laying such high-voltage cables underground considerably stimulated British cable research and development. Because of the very high voltage, the usual cables comprising three paper-insulated conductors cannot be employed. Instead, single-core oil-filled cables are used and are laid in triangular formation to provide the three-phase line. Fig. 10 includes a section of this cable.

A recent development is a 3-core oil-filled cable which will lower the cost of underground high-voltage systems. Another advance is the gas pressure cable, limited sections of which are already in operation in the more important supply areas.

The Grid is controlled at certain selected control rooms, where all switching operations are carried out to meet the changes of load.

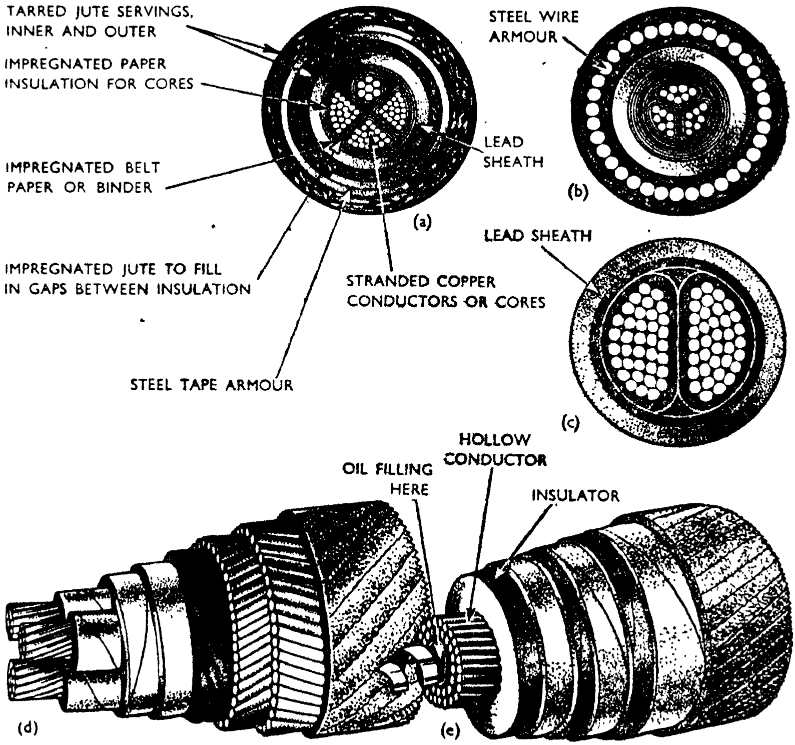
Owing to the high cost of underground systems, where practicable power lines are run overhead. These overhead systems are almost universally employed in rural districts.

As lines, which is the term for overhead cables, are fixed to insulators mounted on poles, it is not necessary for the lines to be insulated, and this reduces the cost.

The material comprising the conductors varies according to the voltage, the current and the mechanical strain which, of course, increases with the length of the span between poles. Extra strain is placed on these wires by high winds, ice and snow. When deciding on the type and size of conductor, all these things have to be taken into consideration.

The commonest conductors for overhead lines are steel-cored aluminium, steel, steel-cored copper, cadmium copper, and hard-drawn copper.

Almost without exception, conductors are stranded. Single-core conductors are only used in rare


TARRED JUTE SERVINGS, INNER AND OUTER
IMPREGNATED PAPER INSULATION FOR CORES
IMPREGNATED BELT PAPER OR BINDER
IMPREGNATED JUTE TO FILL IN GAPS BETWEEN INSULATION
STEEL TAPE ARMOUR
STRANDED COPPER CONDUCTORS OR CORES
LEAD SHEATH
(a)
STEEL WIRE ARMOUR
(b)
LEAD SHEATH
(c)
OIL FILLING HERE
HOLLOW CONDUCTOR
INSULATOR
(d)
(e)

TYPES OF UNDERGROUND CABLES

Fig. 10. (a) Section of a 3-core, low-tension, paper-insulated, lead-covered and steel-tape armoured cable. (b) Section through 3-core, extra high-tension, paper-insulated, lead-covered and steel-wire armoured cable. (c) Twin-core, high-tension, lead-covered U.G. cable; sheathed with a continuous tube of pure new lead. (d) 3-core circular cable, lead covered, compounded jute served, double-wire armoured, compounded jute served overall. (e) Single-core, oil-filled cable.

instances where cost is the chief consideration.

Steel-cored aluminium conductors are used throughout for the overhead lines of the Grid scheme. The standard size is 0·77 in., with a cross-section area of 0·27 sq. in.

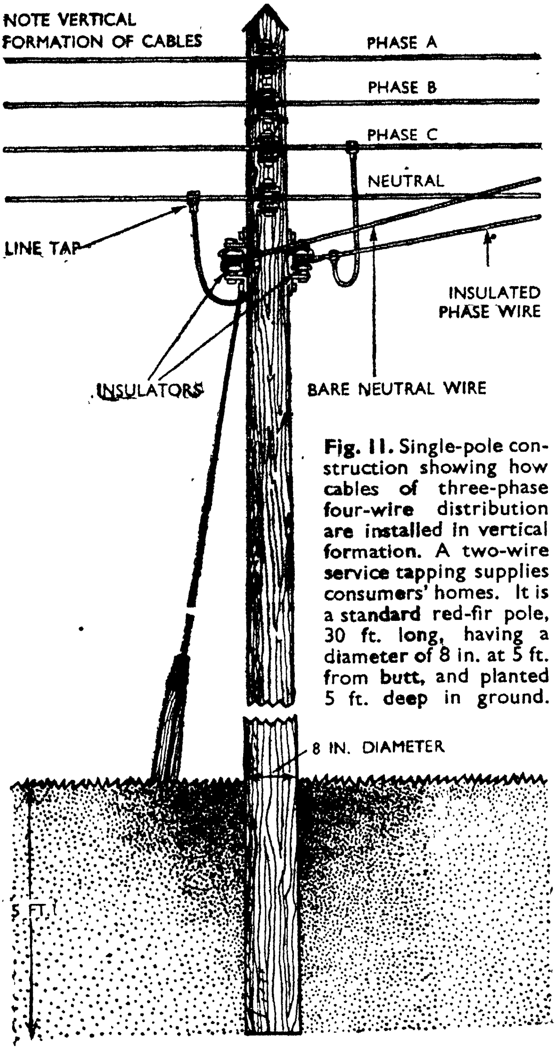


Fig. 11. Single-pole construction showing how cables of three-phase four-wire distribution are installed in vertical formation. A two-wire service tapping supplies consumers' homes. It is a standard red-fir pole, 30 ft. long, having a diameter of 8 in. at 5 ft. from butt, and planted 5 ft. deep in ground.

Voltage Drop

Conductors of steel, steel-cored copper and cadmium copper are used for the normal high-voltage systems of 6·6, 11 and 33 kV. Cadmium copper is the most expensive of the three, but the voltage drop per unit length, for a given current, is the lowest. Steel, on the other hand, is the cheapest and also has the highest voltage drop per unit length.

Steel and steel-cored copper conductors are installed on the cheaper systems. For instance, steel conductors are adopted for small extensions off the main distribution schemes.

Hard-drawn copper lines are almost universally accepted for overhead low-tension distribution systems operating at up to 450 V.

Latticed steel pylons are usually erected for EHP systems. For the Grid scheme, of course, these pylons are used on a wide scale.

In practically all other cases the poles are of red fir. To ensure that these poles will last for a number of years they are impregnated with creosote applied under pressure. Good poles have been known to last up to fifty years. Reinforced concrete uprights are used to a lesser extent. Poles are constructed in four main types.

Single-member poles (Fig. 11) are ordinary poles and are used in all positions where there is no undue tension or stress and where no transformers or switchgear are to be mounted on them.

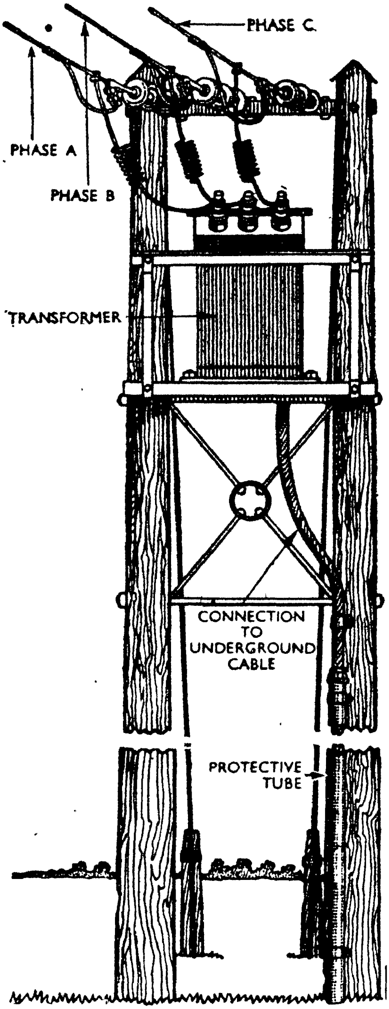


Fig. 12. "H" pole supporting transformer. These poles are used where there is no undue tension or stress.

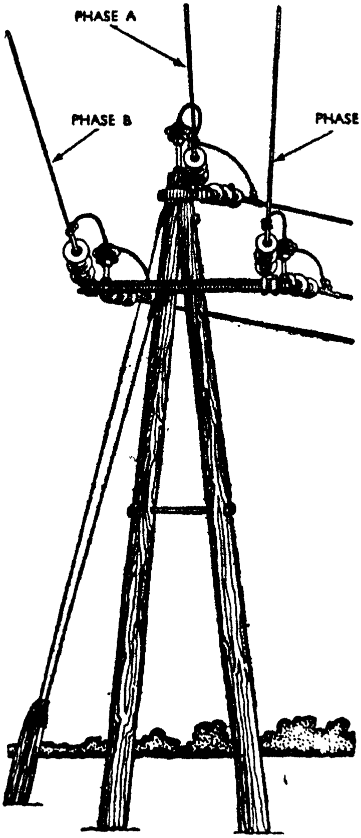
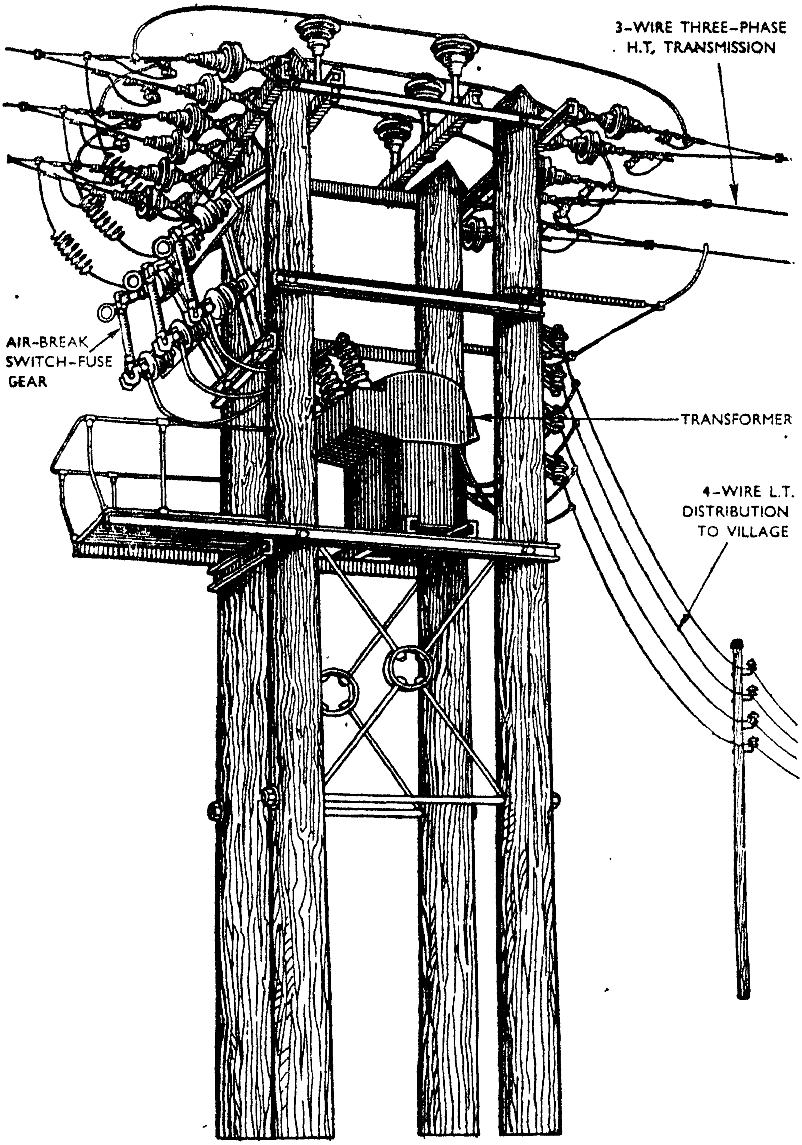


Fig. 13. Pole utilized for three-phase three-wire high-tension transmission where route of cables turns at an angle.

"H" poles (Fig. 12) comprise two single poles strapped together by steel or wooden cross-pieces and are used chiefly where transformers and switchgear are to be mounted on them.

"A" poles (Fig. 13) consist of two member poles spaced at the base and joined at the top, held by of the letter A. These are chiefly where bends in the lines


3-WIRE THREE-PHASE
H.T. TRANSMISSION
AIR-BREAK SWITCH-FUSE GEAR
TRANSFORMER
4-WIRE L.T. DISTRIBUTION TO VILLAGE

FOUR-MEMBER POLE FOR SPECIAL PURPOSE

Fig. 14. Four-member pole construction, which comprises two "H" units in the form of a square joined by cross-bars, with transformer, switchgear and fuses. L.T. four-wire three-phase distributor is tapped off transformer secondary to supply a village. These poles are installed where extra-heavy transformers and switchgear are required and the arrangement improves accessibility.

cause strain and single poles would be unsuitable.

Four-member poles (Fig. 14) comprise two "H" units in the form of a square joined by crossbars. They are installed where extra-heavy transformers and switchgear are required, usually at the junction of a number of circuits.

Wood poles for high-tension lines are usually of from 34 to 40 ft. in length and have a diameter of approximately 12 in. at a distance of 5 ft. from the butt (Fig. 11). They are planted to a depth of 7 ft.

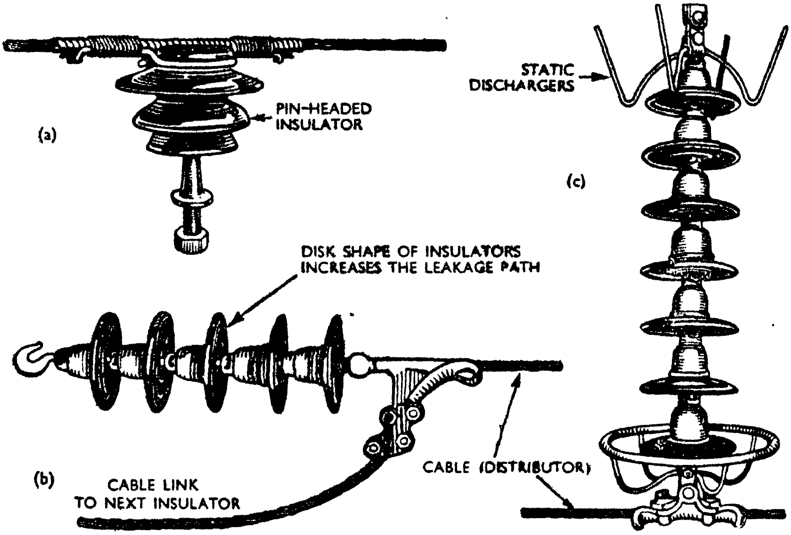
For low-tension lines, poles are from 28 to 30 ft. in length with a diameter of 7½ to 8 in. at a distance 5 ft. from the butt and are planted to a depth of 5 ft.

Overhead lines must be installed at minimum heights, particularly where they cross roads and railways. Standard codes of practice have been laid down. For instance, over fields and similar ground, the lowest conductor must clear the ground at a minimum height of 17 ft., but where roads are crossed the minimum height is increased by 2 ft., which gives a clearance of 19 ft. It is at these positions where poles of 30 ft. in length are used.

Insulators

The insulators to which lines are fixed are the only insulation employed on overhead schemes. It is very important that they should combine good mechanical strength and high insulating properties.

The insulators most commonly used in this country are British-made porcelain, glazed brown. These have been found to be the best possible from all points of


STATIC DISCHARGERS
PIN-HEADED INSULATOR
(a)
(c)
DISK SHAPE OF INSULATORS INCREASES THE LEAKAGE PATH
(b)
CABLE LINK TO NEXT INSULATOR
CABLE (DISTRIBUTOR)

THREE FORMS OF INSULATOR

Fig. 15. Insulators used in modern overhead electricity distribution and transmission schemes. (a) Pin-type insulator, with conductor made fast by binding. (b) Straining type, five-unit, used where bends encountered have wide angles and lines are strained. (c) Suspension insulator, for high voltages.

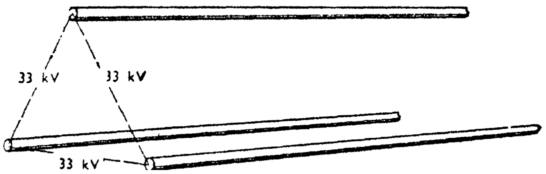


Fig. 16. Triangular formation of conductors on overhead systems leads to good electrical balance. Voltages between pairs of conductors are all equal.

view. There are three main types, viz. pin, straining, suspension. Pin types (Fig. 15a) are used extensively for L.T. lines. They are also employed on H.T. transmission where the poles are placed in a straight line and, to a lesser extent, where small angles are encountered. The voltages of the H.T. transmission schemes where pin insulators are employed are 6600, 11,000 and 33,000.

Straining insulators (Fig. 15b) are used on H.T. transmission schemes for voltages up to 33,000 V, where the bends encountered have wide angles. They are also employed where the lines are strained, that is, about every half-dozen poles, where these insulators take the strain of that section of the line, leaving the pin insulators on the intermediate poles just to carry the weight.

Suspension insulators (Fig. 15c) are utilized for all H.T. transmission schemes operating at voltages above 33,000, where the poles or pylons are planted in a straight line. Straining insulators are inserted at regular intervals.

Although, as mentioned above, pin insulators may be used for transmission schemes working at a pressure of 33,000 V, suspension insulators are preferred where cost is not one of the chief considerations.

The insulators of high-voltage transmission schemes are so arranged on the poles that they form a triangle. The lines run in what is known as triangular formation (Fig. 16). This construction has proved the most economical, particularly as the voltage or electrical stress between all conductors is equal. For L.T. distribution, where the electrical stress is slight and where simplicity of construction and lowering of cost are of more importance, conductors are installed in a vertical formation, as shown in Fig. 11.

Earth Wires

It has been mentioned that a continuous overhead earth wire is installed and fixed at the apex of each steel pylon on the Grid. This wire not only reduces lightning risk but also acts as a continuous earth connection of all metal-work.

This continuous system is known as bonding. Every quarter of a mile the continuous earth wire is earthed by running a wire down the pylon to terminate at a copper plate sunk well in the ground.

H.T. schemes having wooden poles are often similarly fitted with a continuous earth wire which is also earthed each quarter mile. Although the best position for this continuous earth wire is at the apex of the pole, in some schemes it is run 3 ft. below the bottom conductor. Although this position is not the best from the lightning point of view, should one or more of the conductors break they immediately come into contact with the earthed wire and so prevent damage to gear. Should the line subsequently fall on to a person, an animal or building, no damage can be caused, as the line is now dead.

It is possible to bond a system without having a continuous earth wire. Instead, the structural metalwork of each pole may be bonded by a bare, soft copper conductor which runs down to an earth plate.

Where the ground is unsuitable for earthing—such as too dry a soil—an overhead earth wire must be used and the best portions of ground selected for the earth plates. Wherever possible these plates are situated at positions not more than a quarter of a mile apart.

Distributors

L.T. distribution cables are run along the streets as near as possible to the points to be supplied. These distributing cables (known as distributors) are tapped at convenient positions. Similar lines, known as service lines, are extended to the various premises.

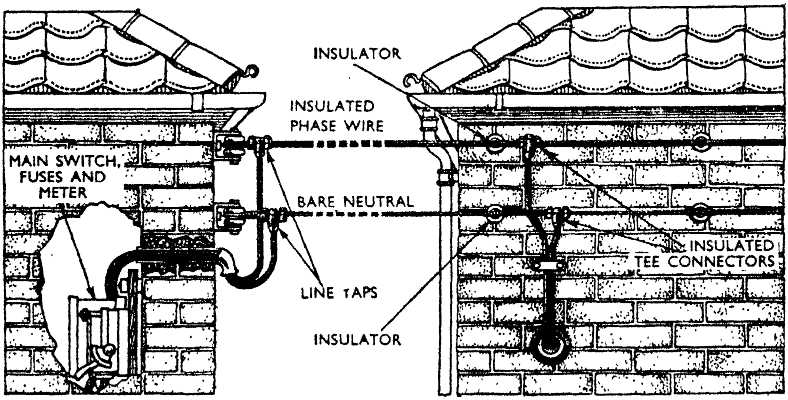
Houses built close together or in terraces are supplied from one service (or tapping off the distributor) and tappings off this service are then made to each house.

Fig. 11 shows a typical tapping off a distributor at a pole situated near the premises to be supplied. From the first house to which the service cable is connected, cables may be run along the walls of the houses as near the eaves as possible. This type of distribution is known as under-the-eaves system, which is illustrated in Fig. 17.

Bare Neutral Wire

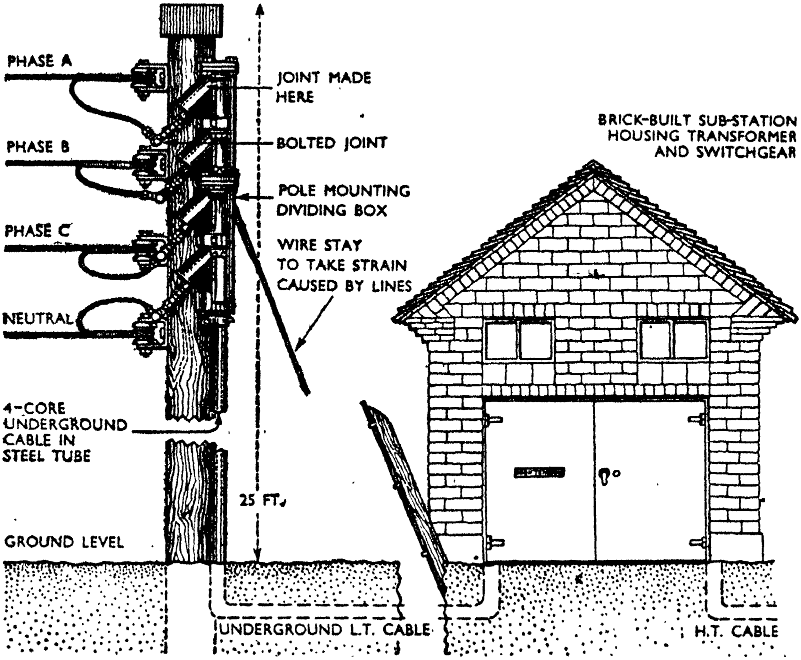
As shown, the phase wire is insulated but the neutral is bare. It is not necessary to insulate the neutral, because this is at earth potential. Therefore, should any one come into contact with it he or she would not receive a shock.

At each point where the distributors are tapped a suitable joint is made. This comprises a junction box for the phase wire and a line tapping for the neutral. A porcelain bell-mouth tube is placed in the brickwork and the insulated twin



HOUSE-TO-HOUSE SERVICE BY UNDER-THE-EAVES SYSTEM

Fig. 17. Two insulated tee connectors in use on a phase wire and neutral respectively. Connectors are not fixed to the wall but are held in position by the cables.


PHASE A
PHASE B
PHASE C
NEUTRAL
4-CORE UNDERGROUND CABLE IN STEEL TUBE
GROUND LEVEL
JOINT MADE HERE
BOLTED JOINT
POLE MOUNTING DIVIDING BOX
WIRE STAY TO TAKE STRAIN CAUSED BY LINES
25 FT.
BRICK-BUILT SUB-STATION HOUSING TRANSFORMER AND SWITCHGEAR
UNDERGROUND L.T. CABLE
H.T. CABLE

CONVERSION FROM OVERHEAD TO UNDERGROUND SYSTEM

Fig. 18. Illustration shows conventional method of feeding a four-wire three-phase distribution system from a brick-built sub-station. Note simple method of jointing and protection given to insulation of underground cable by enclosing it in a galvanized steel pipe for a distance of 8 ft. above the ground.

service wires run through the wall to the meter position.

In the diagram, the meter position is shown as in the upstairs room. This location is often adopted to shorten the length of the service. Where the meters, main switches and fuses are installed on the ground floor, it is necessary to run the service wires down the outside wall.

Semi-detached and detached premises built close together may be supplied by overhead service cables which are strained between houses (see Fig. 17). For isolated houses it is necessary to provide a separate service cable from the main distributors. The tapping is usually made on the nearest pole position.

Rarely do overhead distribution systems consist solely of overhead lines. G.P.O. telephone wires, railway lines and parts of villages, where overhead lines would be undesirable, all necessitate that parts of the system must go underground. Also, where the line is to feed a main sub-station, lengths of underground cable are used.

Dividing Boxes

Fig. 18 illustrates how conversion from overhead to underground is carried out by the adoption of special dividing boxes. The overhead lines terminate at insulators fixed to the terminal pole in the line. Connections are taken to the dividing boxes. Underground cables run from the boxes down the pole and underground either to a further pole or to the sub-station as the case may be.

To prevent damage, this cable is usually enclosed in a galvanized steel pipe for a distance of 8 ft. above the ground.

Underground Cables

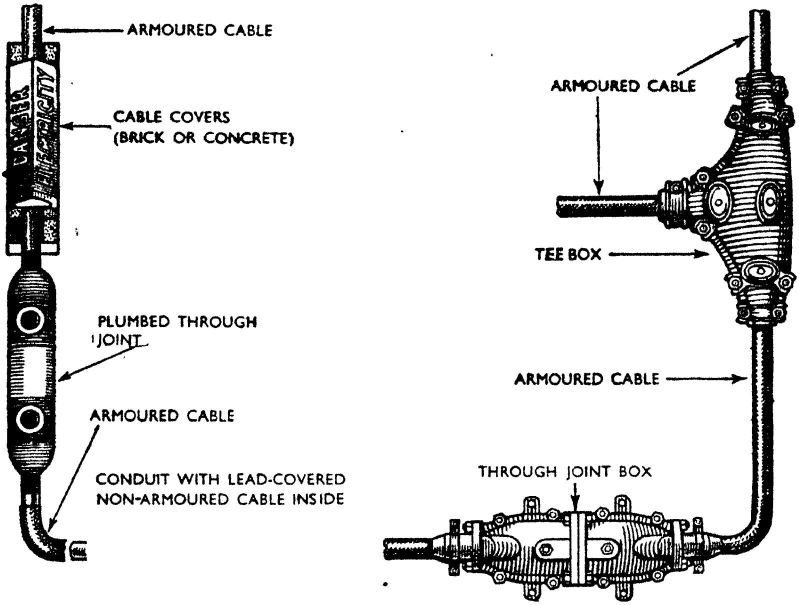
Up to now overhead cables have been referred to as lines. Now the word cables will be employed, as that is the usual term in connection with underground systems.

Fig. 1b gives typical examples of underground cables. The conductors are usually of tinned copper. The insulation, and the covering to prevent the conductors from mechanical damage, vary according to circumstances.

Paper insulation is most usual. It is impregnated with special oil to prevent the absorption of moisture, which would destroy the insulating properties. Over this insulation is a continuous lead sleeving which retains the oil. All joints are mechanically and electrically sound. The sheath is earthed to prevent leakage current passing from section to section.

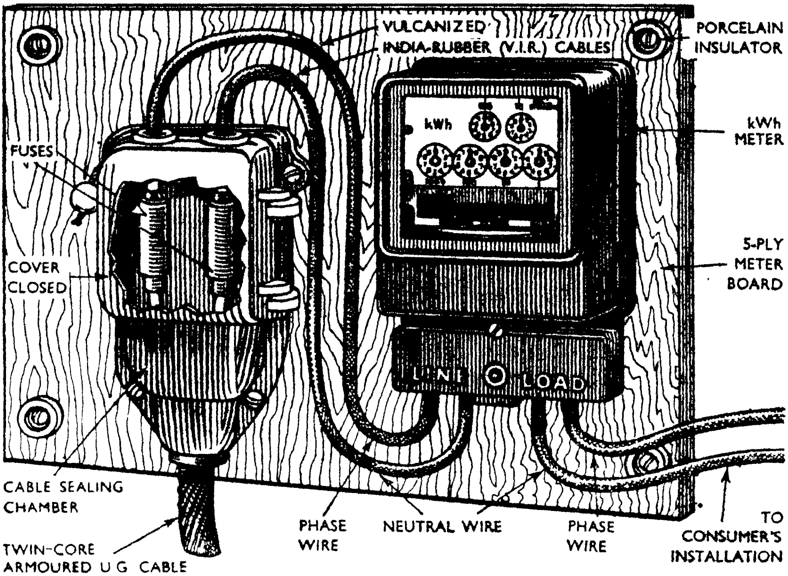
An insulation in another type of cable consists of an oil filling (Fig. 10e), and a further development, that of gas pressure, provides an even better insulation.

Cables are sometimes armoured with steel tape or steel wire to protect them from mechanical



HOW UNDERGROUND CABLES ARE JOINTED

Fig. 19. Various methods of jointing underground cables by the use of joint boxes and plumbed joints. Earthenware covers for lead-covered cables and conduit for non-armoured cables which are laid direct in the ground are also shown.



PREVENTING OIL LEAKAGE AT CONSUMER'S END

Fig. 20. It is essential to avoid leakage of oil at the termination of the service cable. Here is a standard sealing box and fuse-box combined, mounted on a 5-ply board, with a house kWh energy meter on consumer's premises fed by underground cable.

damage when laid direct in the earth (Figs. 10a and 10b).

In towns, cables are almost invariably underground, usually under the pavements and footpaths. In this position installation is simplified, repairs are more easily carried out, and damage is not caused by heavy traffic, as would be the case were the cable under the road.

H.T. cables or feeders supplying sub-stations are laid in earthenware or fibre ducts. The ducts or conduits are first laid in trenches of a depth of about 20 in. and the cables afterwards drawn through.

Where railways and tramway systems pass above, iron pipes are used instead of earthenware or fibre. Paper-insulated lead-covered unarmoured cables (P.I.L.C. cables) are usually employed for this purpose. Fig. 10c shows a sectional view of a P.I.L.C. cable, while Fig. 19 shows a section of earthenware conduit.

L.T. cables, on the other hand, are generally laid direct in the ground. This is not only less costly but also makes it easier to tap the cable for the house services. These cables are laid to a depth of 12 to 24 in., depending upon the nature of the ground and whether laid under footpaths, grasslands or roadways and suchlike.

Laying Direct

Paper-insulated lead-covered steel wired or steel taped armoured cables (P.I.L.C.S.W.A. and P.I.L.C.S.T.A. respectively), which are covered overall with hessian, are employed for laying direct. As a further protection, tiles are placed over the cables to prevent damage during excavation.

Owing to its greater pliability, steel-wire armouring instead of steel-tape armouring is employed where there is a possibility of ground subsidence.

Jointing

At all points where consumers' premises have to be supplied it is necessary to tap the distributor. Where joints are made in paper-insulated cables, care has to be taken that the joints are properly sealed to ensure that the oil with which the paper is impregnated does not seep out and allow moisture to take its place.

Joints may consist of either the plumbed joint, carried out on the spot, and which is similar to an ordinary lead water-pipe joint, or special joint boxes may be used. Fig. 19 gives two typical straight-through joints and a T joint where both methods are applied.

It is not only necessary to ensure that the leakage of oil does not occur at the joint itself, but the termination of the underground service cable upon the consumers' premises must also be oil-tight. Here a sealing box is provided from which conductors are taken into the house. Fig. 20 illustrates this type of box, complete with fuses mounted on the same board as the consumer's meter.

An illustration has been given of the layout of a typical transmission and distribution scheme. Sub-stations are used for transforming the high-tension current at 11,000 V down to the operating pressure of 400/230 V, this being the standard voltage adopted in Great Britain. In practice, a large number of these transformer stations, or sub-stations, are necessary at suitable points. From these positions the distributing cables are taken to consumers' premises along the road.

Sub-stations may be of brick or may consist of an iron housing, known as a kiosk, situated just off the pavement and often painted green. In rural areas similar sub-stations consist only of the transformer, switchgear and protective apparatus, all mounted on the pole.

Sub-stations house transformers for reducing the pressure of the current from that used for transmission (which may be 6600 V, 11,000 V, 33,000 V) down to the operating voltages of 400/230 V. (Intermediate sub-stations on the system reduce the voltage from, say, 132,000 down to 33,000 or 11,000.) Other apparatus comprises high-tension switchgear, circuit breakers and protective apparatus for cutting off or isolating the H.T. supply and also L.T. switchgear for isolating one or more of the L.T. distributors.

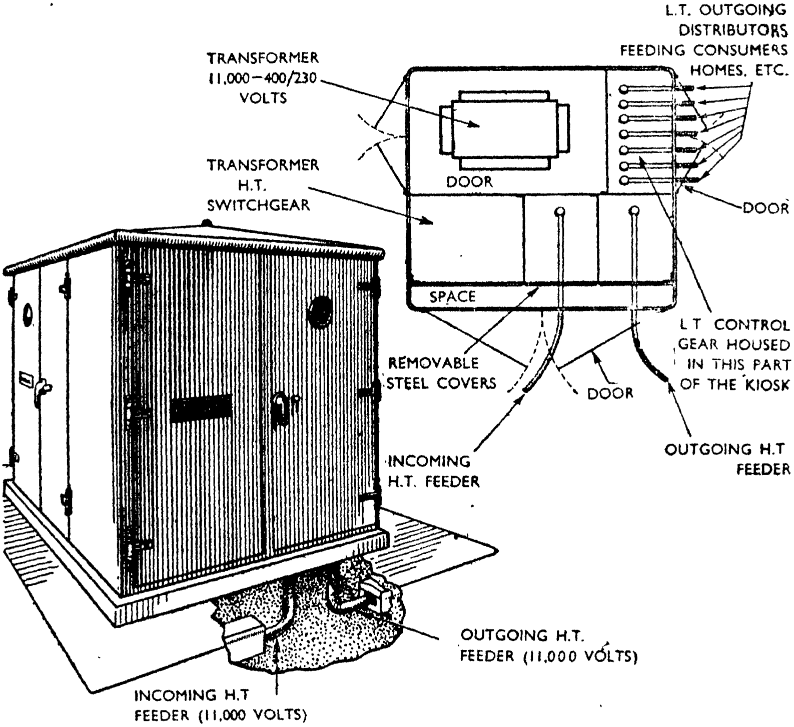
Sub-station Equipment

In most sub-stations fuse units are installed for controlling L.T. distributors or individual distributing circuits or ring mains. The function of these is similar to that of a large fuse board, but instead of supplying the internal circuits of a house they control the circuits forming the distribution scheme.

Some sub-stations also house meter equipment for measuring the amount of electrical energy in kWh consumed on that part of the system. Fig. 21 shows a typical outdoor steel kiosk sub-station.

At least one brick sub-station is incorporated in a rural scheme, which is usually provided to transform the EHP supply taken from the Central Electricity Board's Grid scheme to operating L.T. voltage.

Switchgear is a very essential part of a distribution system. By carrying out various switching operations the supply engineer is able to control all sections of the supply network at one or more convenient points. Also, overloads due to breakdown of the installation and obstructions of the line result in the automatic operation of switchgear or circuit-breakers before damage reaches any magnitude.


TRANSFORMER 11,000–400/230 VOLTS
TRANSFORMER H.T. SWITCHGEAR
L.T. OUTGOING DISTRIBUTORS FEEDING CONSUMERS HOMES, ETC.
DOOR
DOOR
SPACE
REMOVABLE STEEL COVERS
DOOR
L T CONTROL GEAR HOUSED IN THIS PART OF THE KIOSK
INCOMING H.T. FEEDER
OUTGOING H.T FEEDER
OUTGOING H.T. FEEDER (11,000 VOLTS)
INCOMING H.T FEEDER (11,000 VOLTS)

TYPICAL OUTDOOR KIOSK-TYPE SUB-STATION

Fig. 21. Two H.T. feeders form part of a "ring" main transmission scheme. The transformer reduces the voltage of the supply from 11,000 V to 400/230 V. The low-tension supply is at 400/230 V and it is distributed by the cables as shown.

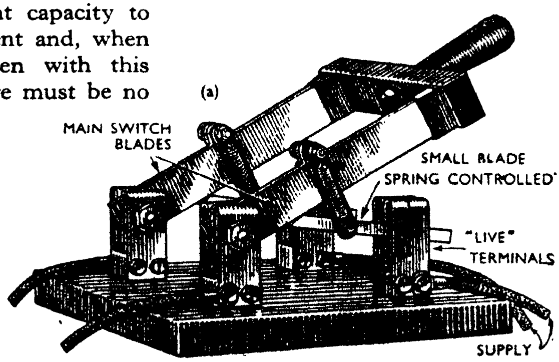
There are two main types of switchgear, the switch and the circuit-breaker. The latter is used chiefly for interrupting the current when it exceeds the normal capacity of the system. Circuit-breakers may also be used for breaking circuits under normal conditions. The operation and functions are more fully described a little further on in this chapter.

Switches, on the other hand, are used either for breaking a circuit where current is within the normal capacity or for breaking a circuit where no current is flowing. Where used for the latter purpose, switches are called isolators. Two forms of switchgear are in general use today: air-break switches and oil-break switches.

The original type of air-break switch was the open-knife type which, as its name implies, resembles the opening and closing of an ordinary clasp knife. Fig. 22a illustrates the operation of the simpler type of knife switch.

The main essentials of a switch are that the blades and contacts must be of sufficient capacity to carry the total current and, when the circuit is broken with this current flowing, there must be no arc or flash which will burn the contacts of the switch.

Arcing of the current upon the opening of a switch can be prevented, within limits, by opening the contacts with an extremely quick break action. As this is not possible by manual methods, spring control is provided. In the switch shown in Fig. 22a, each blade comprises two parts, both hinged at one end and bridged by a strong spring at the other. When the switch is opened the first two blades rise but the second two blades leave the contacts only when a given tension of the spring is reached. This



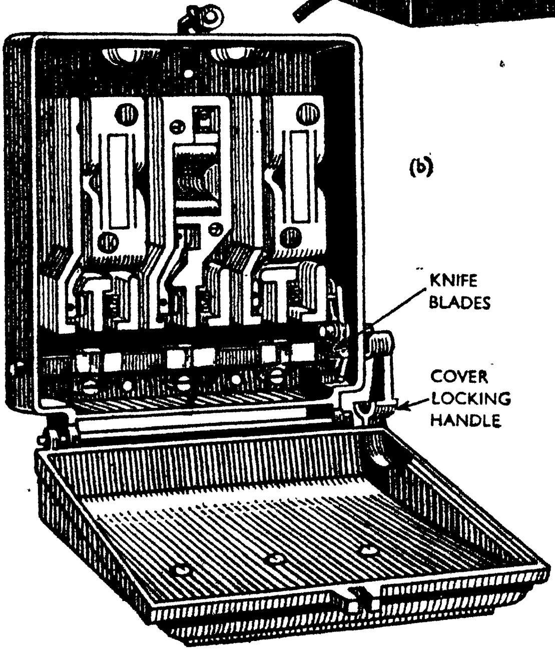


Fig. 22. (a) Simple knife switch. Upon opening the switch the larger blades are released first and tension is placed upon the springs as the small blades remain in the sockets. When the limit of the spring tension is reached, the small blades fly out, giving the switch a positive snap action. In the illustration the switch is about to open. (b) Modern three-phase knife switch and fuses.

provides a quick break action and eliminates arcing.

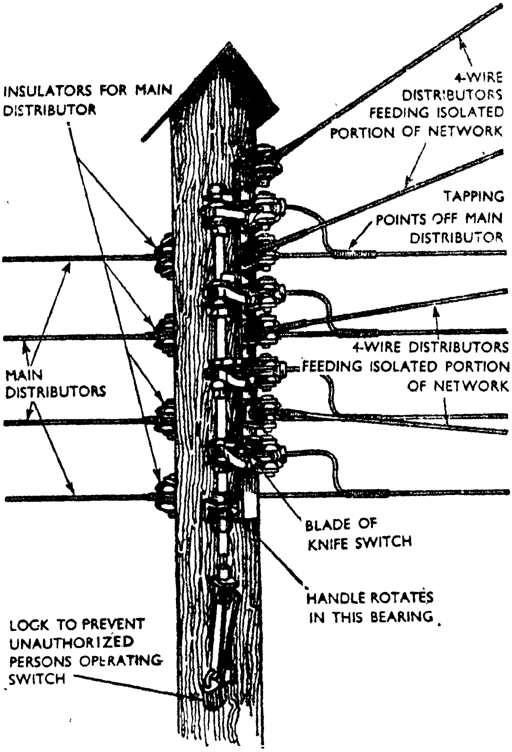

INSULATORS FOR MAIN DISTRIBUTOR
4-WIRE DISTRIBUTORS FEEDING ISOLATED PORTION OF NETWORK
TAPPING POINTS OFF MAIN DISTRIBUTOR
4-WIRE DISTRIBUTORS FEEDING ISOLATED PORTION OF NETWORK
MAIN DISTRIBUTORS
BLADE OF KNIFE SWITCH
HANDLE ROTATES IN THIS BEARING
LOCK TO PREVENT UNAUTHORIZED PERSONS OPERATING SWITCH

Fig. 23. Pole-mounted isolating air-break knife switch. This switch is operated when supply is off to isolated portion of network, owing to fault or to repair work on that part of distribution scheme.

Modern switches are designed with a spring in the handle and this gives a quick make as well as a quick break. These switches are enclosed in iron cases (Fig. 22b) which have a locking device on the operating handle to prevent the cover being opened until the switch is in the "off" position.

Where large currents are to be broken, arcing becomes a more difficult problem. It gives rise to heating and in time burns out the contacts. Air-break switches are, therefore, rarely employed for breaking currents above 400 A.

For larger currents, oil-break switches are used, particularly on high-voltage systems, where they are almost always employed irrespective of the current. The contacts of the oil-break switch are immersed in oil, which prevents the arc from forming as the switch is breaking.

Isolating Switches

Since isolating switches are employed only for isolating circuits when the current has already been interrupted, they are simple pieces of equipment. They ensure that the current is not switched into circuit until everything is ready.

For instance, sections of the supply network or the equipment, such as the transformers, must be isolated from the live supply from time to time for overhauls and repairs. Further, when a portion of the network has been damaged, that portion must be isolated so that the supply may be restored as quickly as possible to those sections where there is no fault. A typical outdoor isolating switch is seen in Fig. 23. Circuit-breakers automatically which has a normal current carrying capacity rating of 100 A, would be used to protect the circuit.

As, however, 100 per cent overload is allowed, this means that though the normal rated capacity is 100 A, the current which will flow before the fuse will melt will be 200 A. Should that amount of current damage the apparatus in the circuit, obviously the size of the fuse wire must be smaller but, as its rated capacity will also be lower, the same dependence could not be placed upon it.

Wire-type Fuses

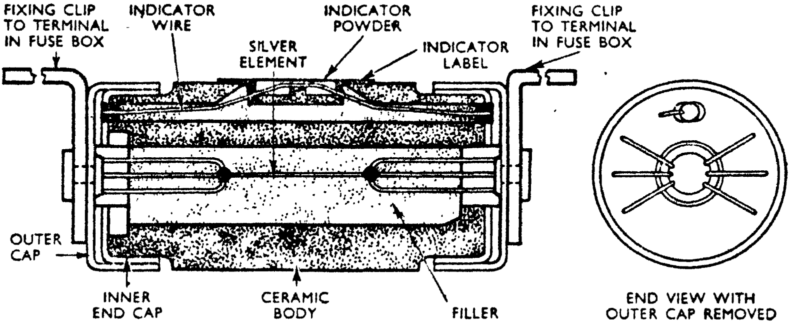
The above is only one of the disadvantages of the wire-type fuse. It has a number of others, as:

(1) The protective capacity is uncertain. This means that no dependence can be placed upon the wire to interrupt the circuit when a given current flows. For instance, although in theory a No. 15 SWG wire should interrupt a circuit when a current of 200 A is flowing, the circuit may be interrupted when a lower current flows or in other circumstances when only a much higher current flows.

(2) The wire fuse is subject to deterioration due to oxidation through the continuous heating up of the tinned copper element. After a relatively short period the current causes the metal to deteriorate and the fuse operates at a lower current than originally rated.

(3) Accurate calibration of the wire fuse is impossible. It is not possible to determine accurately the amount of current which a fuse will carry before it will operate. For instance, a longer fuse operates before one of shorter length. Should the actual wire of the fuse be 2 in., for example, it will carry a higher current before it operates than if the wire were 12 in. long.

Where large concentrations of power are concerned, as in the modern distributing system, it is essential that fuses should have a definite known breaking capacity and also that this breaking capacity should have a high value. Intensive research by manufacturers and supply engineers in this direction has resulted in the introduction of the high rupturing capacity cartridge fuse previously mentioned. A sectional view of the construction is


FIXING CLIP TO TERMINAL IN FUSE BOX
INDICATOR WIRE
INDICATOR POWDER
SILVER ELEMENT
INDICATOR LABEL
FIXING CLIP TO TERMINAL IN FUSE BOX
OUTER CAP
INNER END CAP
CERAMIC BODY
FILLER
END VIEW WITH OUTER CAP REMOVED

HIGH RUPTURING CAPACITY CARTRIDGE FUSE

Fig. 25. This sectional view of a HRC cartridge fuse shows the use of a small element inside a ceramic body. The value of these in protecting motors with their control gear and cables against damage by high kVA faults is widely recognized.

shown in Fig. 25.

The HRC fuse has most of the properties required for the fuse protection of modern distribution systems. The chief of these advantages are:

(1) Its breaking capacity is certain so that each fuse can be accurately calibrated.

(2) Further, the HRC fuse does not deteriorate through use, as the fusing element is of a metal alloy which does not oxidize through heating.

The HRC fuse will carry a current just below its operating current for long periods without changing its characteristics or causing undue temperature rises. While a wire fuse normally operates when current is 100 per cent above the rated capacity, HRC fuses are normally designed to operate when a 60 per cent overload current flows. Some HRC fuses operate when current is only 20 per cent above the rated capacity of the fuse.

It was mentioned earlier that when a circuit , carrying a

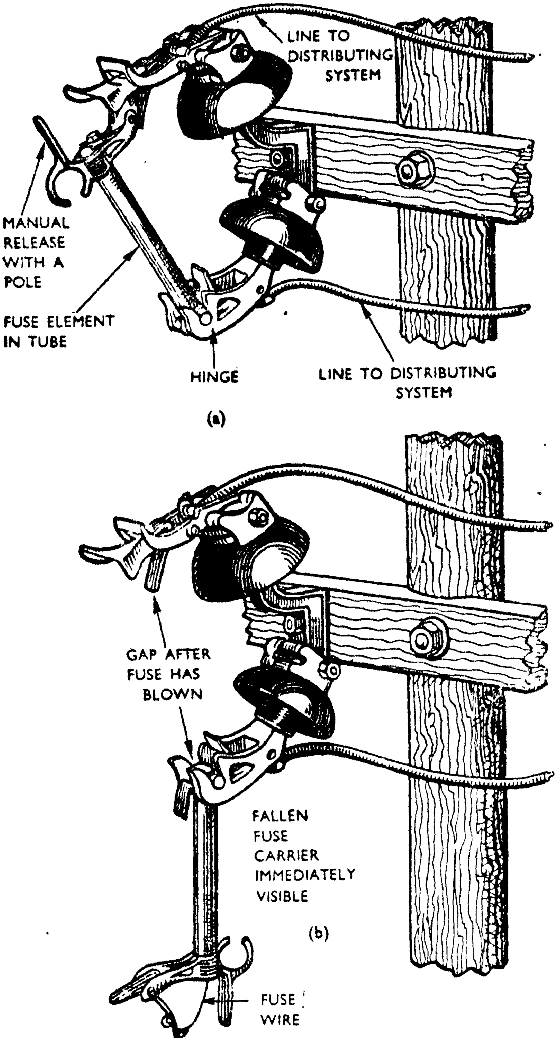

LINE TO DISTRIBUTING SYSTEM
MANUAL RELEASE WITH A POLE
FUSE ELEMENT IN TUBE
HINGE
LINE TO DISTRIBUTING SYSTEM
(a)
GAP AFTER FUSE HAS BLOWN
FALLEN FUSE CARRIER IMMEDIATELY VISIBLE
(b)
FUSE WIRE

Fig. 26. Illustration above is of one member of a swivel fuse. If the distribution is of a three-phase three-wire type, three members, similar to that shown, would be required. (a) Switch fuse, in locked position, and it remains positively locked until the fuse element blows, or the tube is manually released by the operating pole. (b) Tube has been released by the fuse blowing and has dropped down, interrupting the circuit, and any current arc has been broken. Note that the blown fuse can be instantly located.

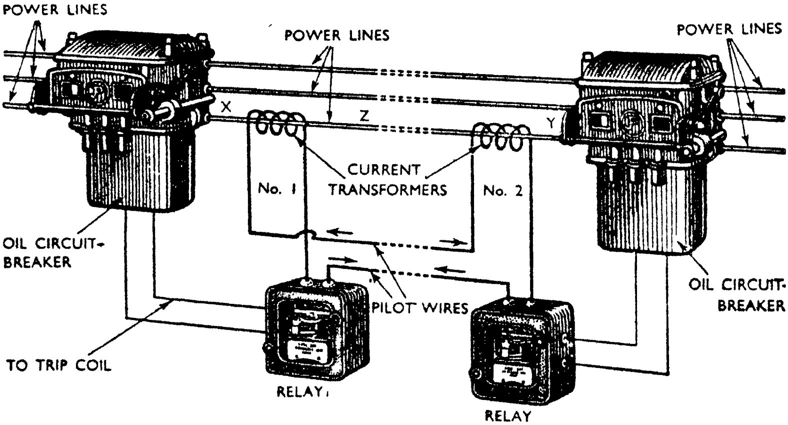
heavy current is broken, an arc is likely to form. The formation of this arc is eliminated in the switch by its utilization of a spring action. As a fuse also breaks a circuit when it operates, the formation of an arc is always probable, particularly where large currents are interrupted. These arcs, once formed, may cause considerable damage to the apparatus in circuit, because heavy current can flow across an arc.

Quenching the Arc

In the HRC fuse the arc is immediately quenched. The fuse is filled with a finely divided quartz powder in which is embedded a silver element. When the fuse operates, a metallic vapour from the silver element combines with the quartz filling and produces a substance known as silicate of silver. Silicate of silver has a high electrical resistance and this prevents the arc from spreading throughout the length of the fuse. Although the HRC fuse provides excellent protection, it is not generally used on the outdoor portions of rural networks, due to the inaccessibility when mounted on poles and the difficulty to determine which fuse has operated. It might be necessary for the electrician to climb a number of poles to examine all the fuses before he had ascertained which one had operated.

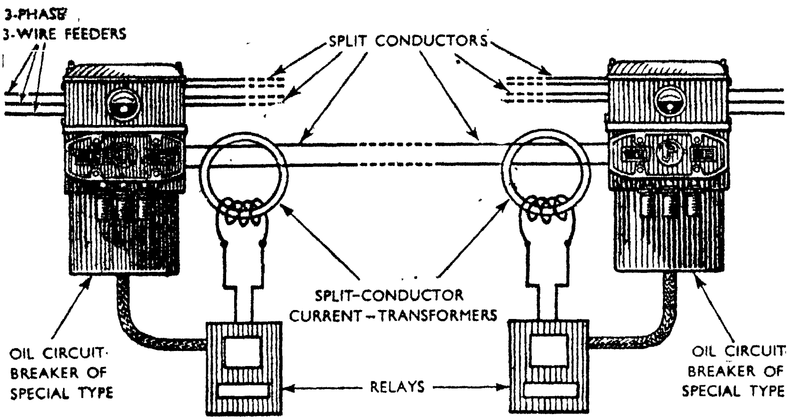
The usual type of fuse on rural schemes is illustrated in Fig. 26. When the fuse operates the holder is released and flies out of its support. This not only ensures that the current is ruptured immediately but shows the electrician at a glance which fuse has operated.

The fuse element is of tin alloy or tin copper. As this type of fuse cannot be depended upon to rupture quickly heavy fault currents, a quick break action must be obtained by operation of the holder. This equipment is, in fact, a fuse switch



RELAY-OPERATED CIRCUIT-BREAKER

Fig. 27. Merz-Price balanced-voltage system is illustrated above. Where the current flowing through point Y is equal to that through X, no current flows through the relays, therefore the circuit-breakers will not operate. Should a fault develop in line at point Z, and a heavy fault current flow, more current will pass through one current transformer than the other and the relays will operate.



SPLIT-CONDUCTOR PROTECTIVE SYSTEM

Fig. 28. Current in each line or feeder is carried by two conductors of equal resistance; a special 6-core cable is, therefore, necessary. The current transformers each have a primary winding which is split into two parts of equal resistance, the ends of which are connected to the split conductors of the feeder.

since the holder actually has a switch action and may, indeed, be operated by hand while the fuse is still intact.

The high current capacity of present-day circuits has made it imperative that protection be afforded to the distribution equipment from faults and overloading. This protection is usually secured by the automatic operation of the circuit-breaker.

A circuit-breaker is fitted with a trip coil consisting of a coil of wire wound over an iron core in which is placed an iron solenoid or plunger. When heavy fault current flows through the trip coil the solenoid or plunger is magnetically attracted into the core of the coil. There it trips a lever and so operates the circuit-breaker.

With high-voltage systems carrying normal heavy currents, trip coils cannot be connected direct in to the supply system. The trip coil current, therefore, is switched on by a mechanical relay which is itself operated by a relatively small current taken from the lines by a current transformer as indicated in Fig. 27.

A variety of types of protective gear is employed, two of which are illustrated in Figs. 27 and 28. Some of them require pilot wires, which are special small wires which connect the transformer secondaries to the relays and carry a current depending on the feeder current.

Split-conductor System

Fig. 28 illustrates what is termed the split-conductor system. Here special current transformers are used, the primary windings of which are split into two equal parts.

As will be seen from the diagram, split conductors have also to be used so that connections may be made to the current transformer. The splitting of conductors is one of the chief drawbacks of this type of system.

An alternative is the Merz-Price system, shown in Fig. 27;

here, two current transformers are coupled to each feeder of the supply system. These transformers are connected back to back so that under normal conditions—that is, when the current entering at point *X* is equal to that leaving at point *Y*—no current flows through the relays. The arrows in this figure indicate the direction of the current under normal conditions.

Should a fault develop at point *Z* and cause current to flow out of the system at this point, the current through transformer No. 1 will be greater than the current through transformer No. 2. Current will then flow through the relays and cause the trip coils on the circuit-breakers to operate.

The fault at point *Z* will then be isolated, as the circuit-breakers No. 1 and No. 2 will both operate.

The split-conductor system operates in a similar manner in that the current transformers are connected back to back.

Protective Systems

Protective systems have both to protect the supply system and the equipment connected to it. Overload conditions may be due either to too much apparatus being switched on or to a fault in the system such as leakage to earth.

Protective gear must be sensitive enough to operate quickly when fault conditions arise. On the other hand, they must be stable and not operate under normal conditions. Otherwise unnecessary inconvenience is caused to electricity consumers due to the premature operation of circuit-breakers.

Overhead distribution schemes must be protected from lightning. Considerable damage has been caused where protective equipment is inadequate or absent. Modern equipment has resulted in a great reduction of lightning faults.

The potential difference between a lightning flash and the earth is of the order of millions of volts. When lightning strikes a line, therefore, the voltage in that line is increased very considerably. Assuming the line forms part of a H.T. distribution system normally operating at a pressure of 11,000 V, the equipment, including the insulators, cannot withstand this extremely high lightning potential.

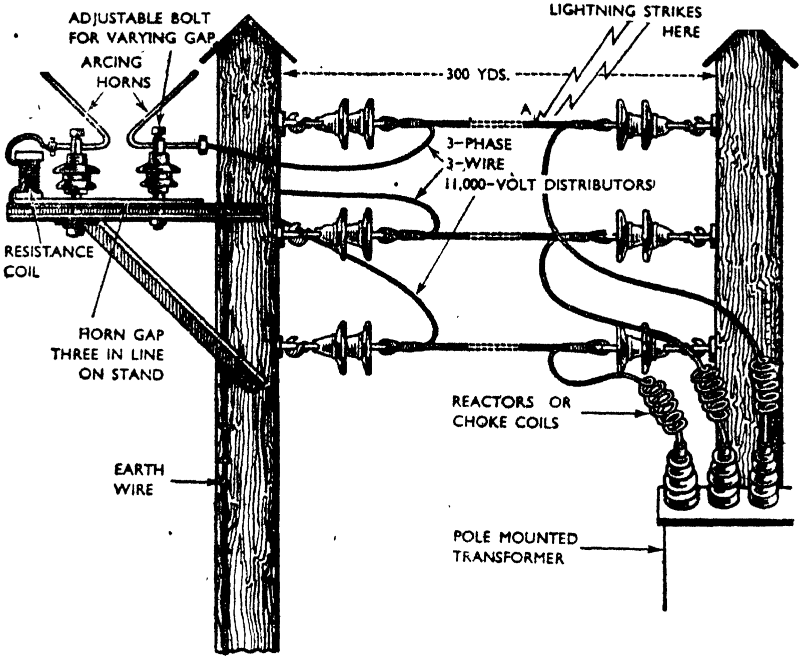
Lightning Danger

The lightning potential follows the easiest and quickest path to earth. This is over the first set of insulators, on to the bracket or pole and down to earth.

As the speed of lightning is very great, at the same instant that the lightning flashes over the first set of insulators it will also flash over subsequent sets down the line. The lightning potential will, however, become weaker as it is directed to earth, so that in time its potential is not great enough to flash over insulators some distance away.

Although not high enough at this distance to flash over insulators, the potential is still considerably higher than the normal operating voltage of the system. Should the lightning current be allowed to proceed on its path, switchgear, transformers, and other equipment would be damaged and probably destroyed.

Also, once a flash-over has occurred at any point there is a danger of the actual line current taking the same path. The distributing equipment may be severely damaged; at best, the supply will be interrupted by the operation of the circuit-breaker. It follows, then, that protective equipment in the form of lightning arresters must fill the following functions: it must provide a path to earth for a high-voltage current but prevent the line current from following that same path; during normal times the arrester must be insulated from the system.



HORN GAP AND REACTANCE COILS

Fig. 29. Assuming a point A receives a direct lightning strike, the reactance coils near the transformer check the high potential and prevent damage to the transformer. High-potential lightning jumps the narrow part of the horn gap, heat forces the arc upwards to the wider part, the arc is broken and the flow of current to earth ceases and normal conditions of the system are restored.

A simple lightning arrester comprises an air-gap. High-voltage current will jump this gap and pass to earth, as shown in Fig. 29. While the distance between the elements of this gap must be as close as possible to provide an easy path to earth, it must be sufficiently wide not to allow the normal line current to jump across. The width of gap depends upon the supply voltage.

To prevent the lightning currents reaching very high values and so damaging the pole upon which the arrester is mounted, a resistance is placed between one element and the earth wire.

Having provided a route for the lightning current across the gap and down the earth wire, it is now necessary to prevent the line current from following this path. This is achieved by the adoption of two horns, one each side of the air-gap, as seen in Fig. 29.

The heavy lightning current crosses the gap at the narrowest part, near the base of the horns. Terrific heating is caused by the arc and this gives rise to an upward current of hot air which draws the arc of current upward until the distance between the horns is too great for the voltage to maintain the arc. The arc is broken and the flow of current to earth interrupted and normal conditions restored.

To ensure that the lightning is directed to the arrester and does not pass to the transformer and control equipment, a further precaution is taken. At each transformer position and as close as possible to the transformer, choke or reactance coils are installed.

These coils consist of a continuous length of copper rod wound in the form of a spiral and having an air core. These coils have little effect on the distribution current but their inductance impedes the passage of the sudden lightning surge current.

Inter-connection System

Long periods of shut-down have been largely eliminated by the inter-connection of systems. The most extensive and important system of inter-connection is the Grid, referred to earlier. Supply authorities also construct portions of transmission lines between their different systems. Should the complete system of one authority fail, the whole of the network can be connected by standby switchgear to the other authority's system.

Faults are normally dealt with by isolating the faulty portions. The ring mains method, as shown in Fig. 8, facilitates this. In many instances, however, particularly in rural areas where the sections of overhead lines are spaced widely apart and pass through widely separated villages, the isolation of small sections is not easy.

Assuming a portion of a line breaks down ten miles from the main sub-station, this section would first be isolated by operating the isolating switchgear as described earlier. Supply would then be made available up to that point. Beyond it the system would be "dead."

To retain the supply in that portion up to the position where the fault occurred may necessitate a large number of switching operations, because the dead position might have to be supplied from another portion passing through a wide circuit of villages.

Remote Control

By the adoption of relays and the installation of a system of pilot wires, in the more up-to-date systems, all switching arrangements are carried out from one central control station.

The control engineer is able to sit at his desk and, by pressing certain buttons, complete remote control is effected. A visual indicator showing the whole network and the actual operation of each switch is provided so that the engineer can see at a glance what is happening.

The Central Electricity Board scheme is a perfect example of this method and thousands of miles of telephone lines are rented from the G.P.O., and are used for transmitting electric currents or impulses which operate the relays of the circuit-breakers and other protective equipment.

In effect, control of electricity transmission and distribution systems is now reduced to simple operation where proper equipment is installed. Because of this, long periods of shut-down rarely occur.

CHAPTER 14

ELECTRONIC DEVICES

ELECTRICITY THROUGH GASES. HOW LIGHT IS PRODUCED. LIGHT ANALY WITH A SPECTROSCOPE. PHENOMENON KNOWN AS FLUORESCENCE. T MIONIC EMISSION. THERMIONIC VALVE. RECTIFICATION. EFFECT OF THE GRID. GAS-FILLED VALVE. CATHODE-RAY TUBES. TIME BASE CIRCUITS. CATHODE-RAY OSCILLOGRAPH. ELECTRON MICROSCOPE. PHOTO-ELECTRIC EFFECT. X-RAYS. SPLITTING THE ATOM. TRANSMUTING THE ELEMENTS.

AIR is an insulator; that is to say, for normal voltages, no current will pass at all between two points separated by air. When the voltage is increased, however, and reaches a really high value, the air becomes conducting and a current suddenly flows, making a spark. About 30,000 V are needed to produce a spark between two points an inch apart.

The lightning discharge is an example familiar to us all. Clouds get charged up by the friction of falling raindrops against rising air currents (hence the "mushroom" appearance of the thunder cloud when not interfered with by wind or any other cause), and when the cloud is at high potential with respect to the earth a discharge takes place between cloud and earth, and this produces lightning.

Clouds also become charged in opposite signs, some being positive and others negative. Then discharges take place between clouds as well as between cloud and earth and we get summer lightning.

The shapes of the electrodes between which the air is situated make a difference to the exact value of voltage which must be reached in order to cause a discharge, and we cannot give any precise figures for the voltage needed to produce a spark of any specified length.

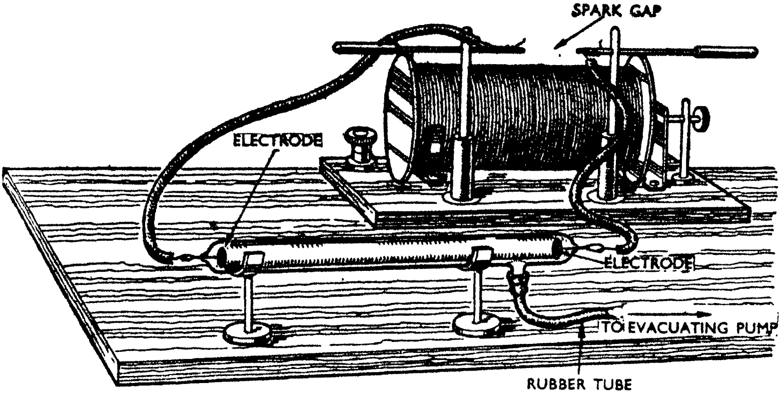
A very high voltage may be created in the laboratory by means of a suitably wound induction coil; one which will give, say, a 10-in. spark is not unusual.

The voltage induced in such a coil is, as we know, proportional to the rate of change of lines of force associated with the winding, and the speed of the "break" of a trembler is usually much greater than the speed of "make." So the induction coil produces a very high electrical pressure which is much bigger in one direction than in the other, and for rough experiments may be taken as unidirectional.

Electricity Through Gases

We can examine very profitably the behaviour of air, or any other gas, when the pressure is reduced, and an electrical pressure applied. The arrangement is shown in Fig. 1, where a glass tube has sealed into its ends two metal electrodes, and an outlet tube to be joined to an evacuating pump.

Using air, because of its convenience, we apply the electrical pressure from the secondary terminals of the induction coil to the electrodes. If these are farther

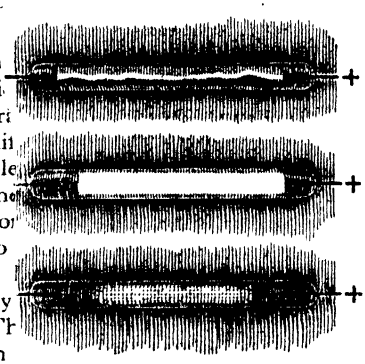


EXPERIMENTING WITH GASES AND ELECTRICITY

Fig. 1. Glass tube with metal electrodes sealed in the ends, and an outlet over which thick rubber tubing can be fixed, may be used with an induction coil for the examination of the behaviour of gases at low pressures under the effect of electricity.

apart than the length of spark obtainable in the outside air, nothing is seen at first.

Now set the pump going. Within a short time, purplish lines of light, a glow, appear streaming from the electrodes, and a few moments afterwards a spark dis- rge passes the whole length of bee tube. This is indicated in int. 2a. As pumping continues, r t ri ti tri dil ple the coi to by Th in ins



2. Three stages in evacuation of ... (a) Showing first spark-like e; (b) positive glow of high ty; (c) final stage when cathode aps are making the glass fluoresce.

the spark steadies and broadens into a continuous band of light of a purplish colour, while a dark space, which steadily lengthens, appears at one end. Close examination will show that at the electrode, where this dark space exists, there is a glow on the electrode surface separated from the electrode itself by a small dark space. But the immediately obvious phenomenon is the long luminous discharge which appears as suggested in Fig. 2b.

If the pumping is continued, and if the pump is a good one, the luminous band splits into striations and the light is whitish instead of purple. The bigger dark space increases in length, and the glow at the electrode separates farther from it and the second dark space is seen to increase in length also; at the same time the column of light decreases in length.

Eventually, the luminous discharge disappears altogether and a greenish light appears on the glass, there being no light whatever inside the tube. In practice, it is difficult to get to this stage, because all the temporary joints needed can no longer stand up to the difference between outside air pressure and inside pressure, and leaks, therefore, result.

Atoms and Electrons

The explanation of all this takes us back to our atoms and electrons. At first the enormous voltage applied is not enough to produce any discharge; nevertheless, the stress is tearing electrons out of the atoms of the electrode material. These atoms, thus deprived, and so positively charged, attract the electrons back again.

As the gas pressure is diminished, there are fewer molecules of nitrogen and oxygen, and a few of the expelled electrons shoot far enough to reach some of these molecules and violently interfere with them, thus creating positively charged atoms which attract other electrons from the electrode. So the gas is becoming very slightly a conductor.

Producing Light

Before considering the phenomena further, we must learn how light is produced. The electrons in an atom are at different energy levels. This means, that two electrons are tied, so to speak, very tightly to the nucleus, and then eight more (if there are as many, of course) are tied not quite so tightly, and then there are eighteen (again, if there are as many in the particular atom) tied still less tightly, and so on through as many "shells" as the atom possesses until we reach the outer electrons.

It is clear that a much greater "splash" of energy is needed to eject an inner shell electron from the atom than to eject an outer electron. If electrons are, nevertheless, ejected from the inner shells, the atom is very unstable indeed, and it is not many millionths of a second before others go from outer shells to the deprived ones.

The energy previously applied to cause the inner deficiency is now released; it appears as a radiation which we call light. All light is created in this way.

We realize that the number of times per second that energy pulses are released in this way will depend on the agitation going on. So light can be produced at very different *frequencies*, i.e. numbers of pulses per second.

"Colour" Sensations

We can recognize difference of frequency to a certain limited extent, and we use the word "colour" to describe our sensations. Red light, for example, is lower in frequency than blue light, and bl lower than violet.

The atoms of any one elem are all the same and will permit emission of light of only cer frequencies which depend on "shells" of the atom. For exam it is impossible to produce light from the atoms of mercu

Air consists chiefly of nitrog and oxygen, there being about f times as much of the former there is of the latter; and the ga are mixed, not chemically co bined.

These facts being grasped, can examine again the discha tube phenomena. At the fi those electrons which travel enough from an electrode are a to interfere with some atoms of t gas and produce sufficient agitati to cause the emission of so light. While pressure is high the electrons do not travel far before they have lost their energy by collision. Then we see the purplish streamers coming out of the electrode. This is visible at high voltages in air at ordinary atmospheric pressure and is known as "brush discharge."

Can we deduce anything from the colour of the light in the brush? Nothing very much, for our eyes have not evolved to such fine sensitivity as to be able to detect slight differences in light frequency. We get the sensation of white light when there is a particular mixture of light of many different frequencies.

The light we see in the brush discharge is purplish and we can judge very vaguely that there is probably a predominance of red and blue and violet, but we cannot say that there is no green and yellow light present; an instrument called a "spectroscope" is needed for such analysis.

Gas as a Conductor

As the gas pressure is reduced, the distance between neighbouring atoms is increased, and, therefore, the electrons ejected from the electrode may travel right to the other electrode, causing some light on the way. The gas has now become a conductor. The sudden decrease of resistance allows a violent discharge to take place, not regular in path because there is still enough gas present to form gray "clouds." The discharge follows the easiest path.

We can now consider the electrodes. The one at the negative end is called the cathode, and is the electron emitter. The one at the positive end is the anode. Of course, these change places during the time the induction coil is producing its interrupted high voltage; but, as previously stated, the pressure in one direction is much greater than that in the other and, if sufficiently preponderant, we can say that the supply is unidirectional.

As the gas pressure is further reduced, there are fewer atoms of gas and at last the electron stream is regular, producing light all along the path except for a small space round the cathode.

Stream of Light

In this gap there is darkness because the electrons meet a stream of positive ions being drawn towards the negative cathode, but kept slightly away from it by the bombardment of electrons. These ions are atoms which have already lost an electron by collision. Not until the electrons go on farther and reach the normal atoms is light produced; therefore, the main luminous column extends from the anode to a short distance from the cathode. The chief effect being one of a stream of light which is the positive column.

As the pressure is reduced still more, and the distance between neighbouring atoms is made greater, the dark space increases in length. At the same time, the number of oxygen atoms still remaining is very small indeed, and the light we see is due more to the nitrogen; so the colour gets less purple and is eventually white and far less brilliant.

At last there is no atom left of oxygen or nitrogen, and a stream of electrons is rushing from cathode to anode; there are no atoms to make luminous. The stream is known as "cathode rays." Where

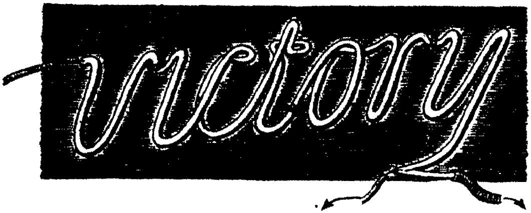


Fig. 3. "Neon" sign using air can be made and demonstrated. The tubing is of glass, heated and bent into shape. Metal electrodes are sealed into the ends. Pumping must be stopped when the glow appears and the end sealed with a screw clip.

they hit the glass, for some of them spread outwards, the green light is produced.

This green light is caused by the interference of the electrons with the molecules which make up the glass. Many solid and liquid substances have the peculiar property of emitting light when bombarded by fast electrons, or by radiation, and the phenomenon is known as *fluorescence*. Again, just as with the gas, the colour of fluorescent light is due to the atomic structure, and has no relation to the normal colour of the substance when viewed in the usual white light.

Ordinary paraffin oil fluoresces under the effect of sunlight, the colour being slightly blue; some red ink fluoresces green in visible light; the quinine in tonic water also fluoresces in bright light. Many substances will fluoresce only under the more energetic influence of fast electrons or of special radiations not yet considered.

Many Light Colours

When at the stage of the very bright positive column, the tube already described can be used as a tubular source of light; and we can have many colours of light, according to the gas used. One of the most startling of all is the gas neon, and discharge tubes with this gas in them at low pressure have been used for advertisement and decorative purposes for some years (Fig. 3).

Mercury vapour gives a brilliant green light; sodium vapour produces a rich yellow-orange light. Combinations of gases can be used, but there is no combination so far discovered which will give white light of sufficient intensity to make commercial production worth while.

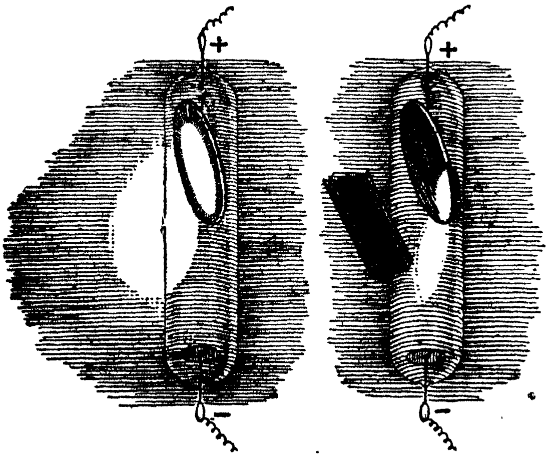


Fig. 4. Magnets will deflect streams of electrons, as we should expect, if our theory is correct. The fluorescence on a special plate is used to show the deflection.

Special tubes for certain effects are preferable to our one tube, which it is difficult to evacuate to sufficiently low pressures. One such tube is shown in Fig. 4. A screen painted with a highly fluorescent material is the anode. In the most usual of the tubes obtainable, the material is white but the fluorescent light is green.

If we approach the tube with the north pole of a bar magnet, as shown also in Fig. 4, the stream of electrons is deflected and the fluorescent target is almost missed. If we work out the direction in which a conductor would move if current in the conventional sense were passing *downwards*, by means of Fleming's Left-hand Rule (Fig. 5), we get the result shown actually by the electrons moving *upwards*, as shown in the illustration. We see that a stream of electrons is, in fact, the same as an electric current, though in the opposite direction to the conventionally accepted flow; and so the electrons are, taking the old descriptive word used long before electrons were discovered, negatively charged.

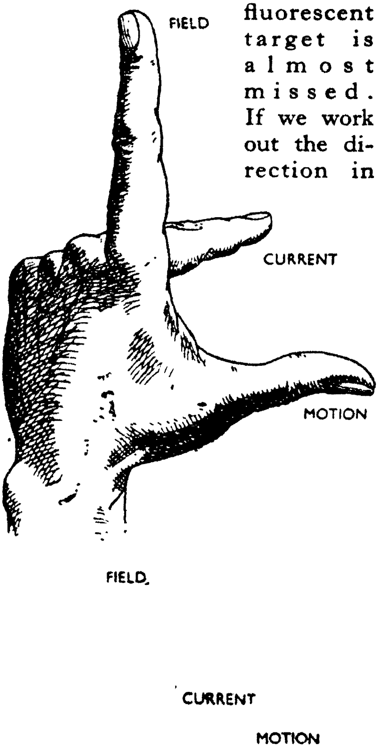


Fig. 5. Fleming's Left-hand Rule. Thumb, first and second fingers must all be mutually at right angles. If the first finger points in the direction of the magnetic field, and the second finger points in direction of the current, then the thumb points the direction of the resultant motion. Below is a diagram indicating the three directions.

Another tube, as shown in Fig. 6, with the anode a metal cross fixed inside the tube and not right at the end, will show us another fact. The electrons (the cathode rays) produce fluorescence on the glass at the end, but the anode stops the stream meeting it and, therefore, there is an absence of fluorescence on the glass, corresponding to the shadow cast; we thus see that the electrons travel in straight lines.

High-speed Electrons

The speed at which they go depends on circumstances, but in all these experiments it is at a rate beyond the experience of all of us, not excluding people in jet-propelled aircraft. For the electron speed is at least 10,000 miles per second.

There is another effect of electronic bombardment which we have not yet considered. It is that when a metal is hit, some of the energy reappears as a radiation of very high frequency, and is quite invisible. This radiation we will consider later; we will pause merely to mention that the rest of the energy of these electron bombardments on a metal appears as heat, and the target gets red hot.

For all the foregoing experiments very high voltages are required. In the case of tubes used for advertising, the high alternating voltage is produced by stepping up the mains volts by means of transformers. The alternation is quick and for each half-cycle the positive column extends through nearly all the tube and so the type of supply has no disadvantage. The secondary voltage of transformers used for these advertising tubes (known so commonly as "neon signs," whatever the gas used) is never less than 3000 and is usually much higher.

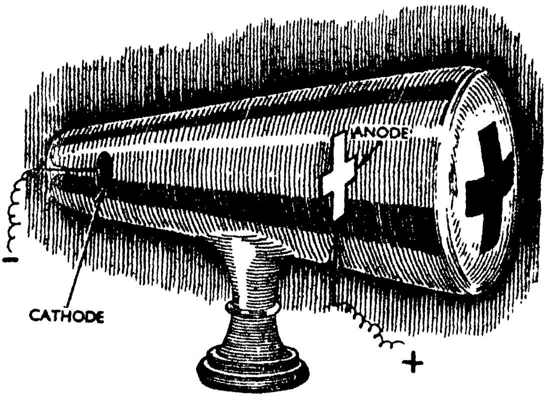


Fig. 6. Cathode rays travel in straight lines, as is seen by the sharp shadow on the end of the tube surrounded by fluorescent light on the glass.

Most of the voltage is used up near the cathode and represents the force needed to tear the electrons out of the electrode and eject them beyond its attractive force.

Clearly, if some means could be found of ejecting electrons from the cathode without the need of the very high voltage, we could, by shortening the length of path between electrodes, get our discharge phenomena with normal voltages.

Such a means has been found. We make the cathode so hot that the agitation is sufficient to eject electrons. An ordinary tungsten wire can be used as a cathode, and heated by passing current through it, the energy being supplied by battery or mains.

The tungsten wire must be white hot before there is any useful emission of electrons (the phenomenon is called *thermionic emission*) and the electrical energy consumed is high. We find, however, that there are some substances which show thermionic emission in a very copious way with much less energy. These substances, in the form of oxide, can be coated on a filament of wire.

Thermionic emission, then, from coated filaments, can enable us to avoid the large cathode fall of voltage experienced in the tubes already described in which the cathode is cold. It remains to be seen how we can make use of this.

Practical Use

The first and obvious use is for lighting. A positive column luminous discharge operable by ordinary mains voltages is a very efficient lighting source. Hot-cathode gas discharge lamps of this sort have become familiar to many people; sodium vapour is used in some and mercury vapour in others. The advantage of the latter is that radiation of high frequency is associated with the light produced, and this radiation will produce fluorescence in many substances.

We see most things by reflected light, and the colour of any object is that of the light reflected by it. For example, a red pillar box appears red because when white light shines on it the paint absorbs some of the light and reflects what is predominantly red; and if we shine light *without any red in it* on the pillar box, this cannot appear red at all.

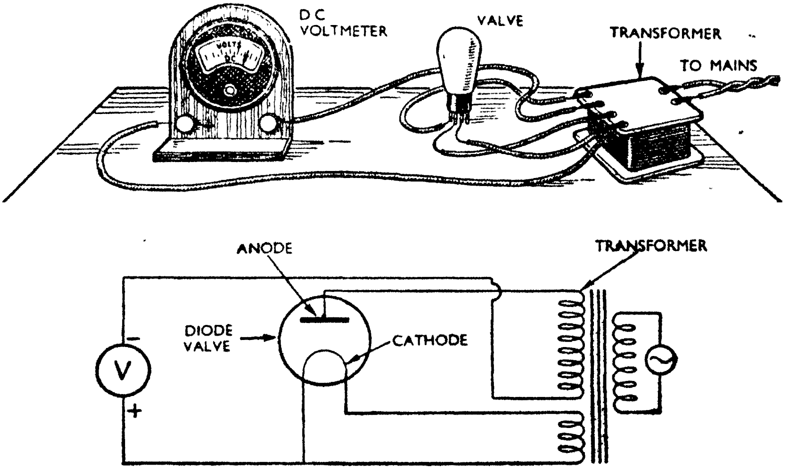
Colour Distortion

In the early days of hot-cathode mercury vapour discharge lamps, this matter of colour was a serious difficulty in shopping centres, where butchers complained that their normally juicy red meat looked a dirty brown. This was because the mercury vapour discharge light has no red in it worth considering, and recourse was had to coating the lamp with a material which would fluoresce with a light containing red, as a result of the invisible high-frequency radiation already mentioned.

Since then the use of hot-cathode discharge lamps has spread and cold-cathode discharge lamps of the neon type, but utilizing fluorescent coatings, have increased in number also for indoor work; one such lamp produces a close approximation to actual daylight.

We come now to yet another device which follows on our discussion and experiment with the glass tube at the beginning of this chapter; then we were not concerned with what happened in the rest of the circuit. But let us suppose that we are not interested in fluorescence or illumination, but instead in the effect of our tube on another part of the circuit.

We then use a hot cathode and a cold anode under such conditions that no fluorescence is produced (non-fluorescent glass) and no luminous column (a very hard vacuum). Such a tube becomes a



RECTIFYING ACTION SIMPLY EXPLAINED

Fig. 7. Here is an illustration which shows how a two-electrode thermionic valve can be used to change A.C. into D.C. The theoretical circuit is given below.

diode, because there are two electrodes, but it and all the others used for associated apparatus are usually called *valves*.

Now, if this valve is included in series in a closed circuit containing an A.C. supply and a moving-coil milliammeter, we find that this instrument registers (if connected the right way round, of course). In other words, we have changed the A.C. supply into unidirectional pulses. This operation is quite aptly called *rectification.*

Rectifying Action

This happens because during the part of the supply cycle when the anode is negative with respect to the cathode, no electrons pass across the valve because the anode repels them. In other words, no current flows, for electron flow is current.

The rectifying action is much used in radio reception. We use it to separate the entertaining part of the incoming signal from the high-frequency part which carries it; that is known as *detection.* We also use it to change an A.C. mains supply into D.C. volts for use instead of a high-tension battery.

A circuit for doing this is given in Fig. 7, which is the same as the one already mentioned except that a voltmeter is used instead of a milliammeter. In addition, the cathode is heated by a small voltage stepped down from the mains by means of a transformer. A step-up is also arranged in the same transformer, so that we can get D.C. volts of the order required.

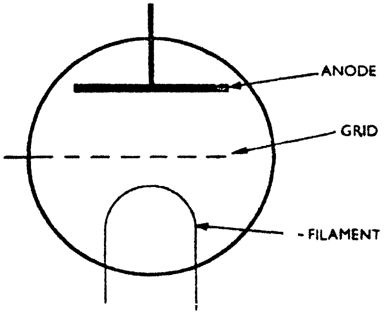


Fig. 8. Theoretical diagram of a triode, directly heated. The three essential electrodes are all clearly indicated.

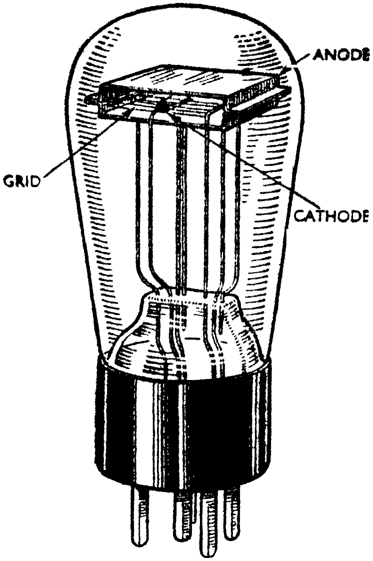


Fig. 9. Simplified diagram of an indirectly-heated triode. Many constructional features are omitted; for example, the assembly of top mica disk with anode.

Smoothing "Ripple"

The moving part of the voltmeter is relatively heavy and shows a steady reading, but actually the plain rectification produces a "ripple" in the resulting D.C. output, and extra apparatus has to be added to smooth out this and make the result as steady as that from a battery. The smoothing circuit is not shown in the illustration because we are not here materially concerned with it at all.

If we add another electrode, the resulting valve is a triode. This extra electrode is in the form of a spiral of wire between the cathode and the anode. In theoretical circuits it is shown as in Fig. 8, if directly heated, though its actual appearance is more like that of Fig. 9. In the latter the cathode is indirectly heated.

Action of the Grid

The effect of the added electrode (the *grid*) is remarkable. It is not a solid obstacle to the electron stream from cathode to anode, but nevertheless it can be supplied with a voltage which can affect that stream; that is, the grid can be used to *control* the electron stream, and so control the current flowing in the circuit of which anode and cathode form a part.

In addition, the grid can be placed very much nearer the cathode than the anode is. A change of, say, 1 V on the grid can make as much change in the anode current as if the anode were itself changed by, say, 20 V. We can use the triode, in other words, to *amplify* voltages applied between grid and cathode; the extra energy being supplied by the high-tension supply.

This is a very useful action, and is the cause of the astonishing results achieved in radio in the past twenty years or so. By suitable circuit arrangements utilizing valves we can magnify the very tiny bit of energy picked up by an aerial and produce volumes of sound; enough to fill many homes and concert halls, if we wish.

The anode is clearly acting as an

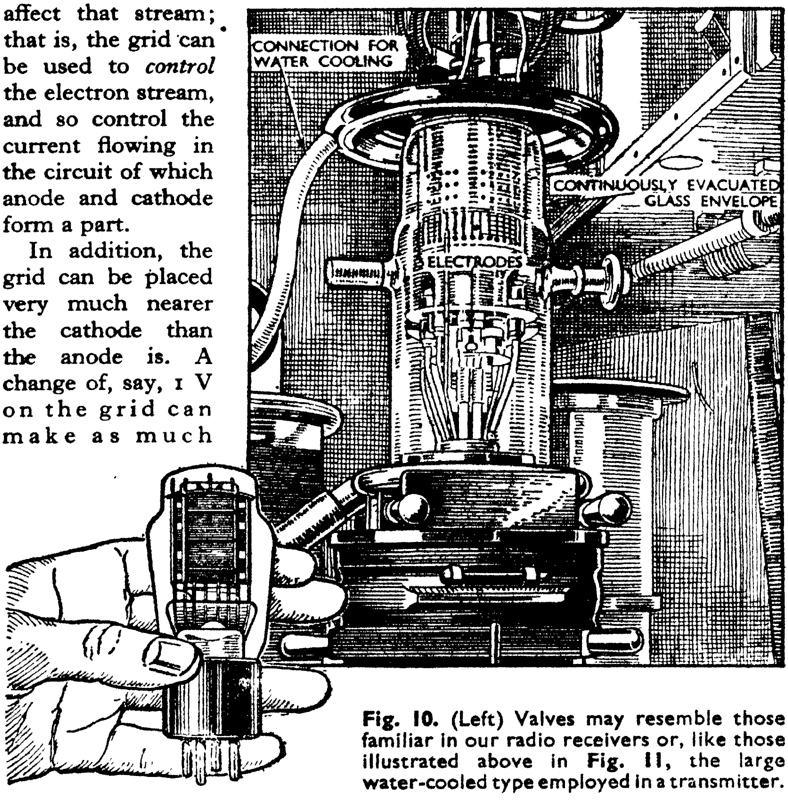

CONNECTION FOR WATER COOLING
CONTINUOUSLY EVACUATED GLASS ENVELOPE
ELECTRODES

Fig. 10. (Left) Valves may resemble those familiar in our radio receivers or, like those illustrated above in Fig. 11, the large water-cooled type employed in a transmitter.

attracter of electrons, and is always made positive by means of a high-tension supply. The power to be conveyed to the loudspeakers is derived from the high-tension supply chiefly, and for really big outputs this supply must be very large. The actual design of valve in mechanical structure is adapted to our needs, and we can have triodes actually smaller than the one shown in Fig. 10, or as big as the one shown in Fig. 11.

Multi-electrode Valves

By adding other electrodes, we can make the valve perform still more complicated actions. There is the tetrode with four electrodes, the pentode with five electrodes, the hexode with six, the heptode with seven and the octode with eight.

In order to make the changing of a valve a simple operation, we usually make the permanent connections of the circuit to a valve holder, which has sockets, and then have the valve made with a base containing pins which will fit into the holder. In the more complex valves, many pins must be available in the base (Fig. 12).

Valve-pin Formation

Unfortunately, the arrangement of pins is not standard, and so it is useless for us to try to memorize any particular pin formations. Instead we group them into the type of formation, four-pin, five-pin, octal, and so on, and then look up a convenient reference table to identify the connections of the valve we are interested in. Some of the valve base arrangements are shown in Fig. 13.

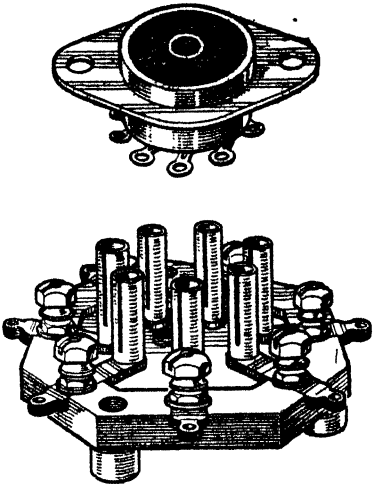


Fig. 12. Valve holders, which are made to suit the various valve bases, vary in design. Here are two, the one at the top being for mounting on a chassis and is an international octal. The one below is for a seven-pin base and is a special "low-loss" type of holder.

The electrodes in the valve are connected to the pins (and sometimes to a top cap as well), and when we plug in a valve we are connecting the electrodes to the circuit. The ordinary 2-V triode has a four-pin base. The two symmetrically placed are for the filament connections; the one between them is the grid connection; and the staggered one, farthest away, is the anode connection. This staggering ensures that we cannot plug in the valve the wrong way round and perhaps in such an event connect the high-tension supply across the filament. If the valve is indirectly heated, then an extra centre pin is used for the separate cathode.

The current obtainable from a small triode is very small (a few milliamperes) and we can, if we like, introduce some gas. The bombardment of the atoms of the gas by the electrons produces light, as we would expect, and at the same time it produces extra electrons by tearing them out of the atoms, which thus become ionized, i.e. electrically charged. (Sometimes the word "ionization" is given as the explanation of the light emitted in a discharge tube, but the acquisition of charge is not absolutely necessary to the agitations required to produce light, though it is true that usually any atoms made to emit light under electron bombardment will also become ionized.) The extra electrons make more current.

In such a gas-filled valve, often known as a soft valve, the grid can be used as a control, not only of the anode current but of the very existence of any such current at all. If a circuit is made, which includes the grid and cathode, then when the grid reaches a certain critical voltage it will suddenly permit the electron stream to pass and then ionization takes place, light is emitted, and a comparatively heavy current at once flows.

This trigger effect of a gas-filled relay is utilized in industry and the laboratory as a method of critical control of current; critical because the valve operates only when a certain voltage is reached. The actual value of this voltage depends on the dimensions of the electrode assembly and the quantity and nature of the gas used. The process of lighting up is sometimes called "ignition," and so the critical grid value is called the "ignition voltage."

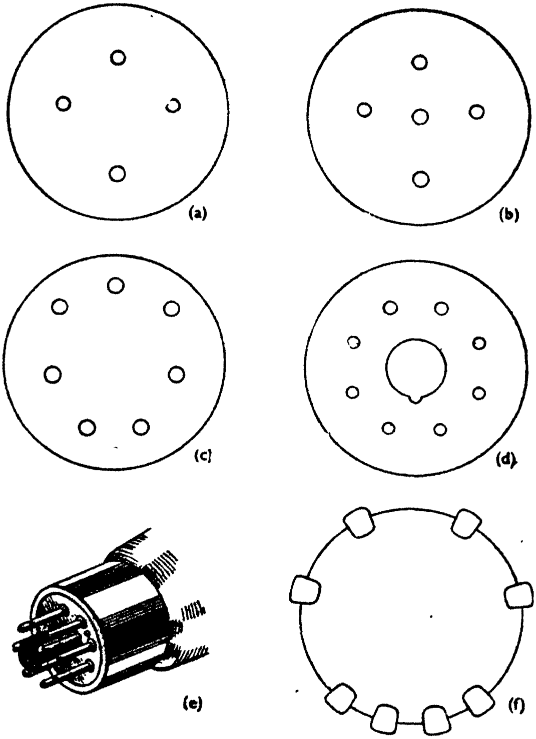


Fig. 13. Six of the commonest types of valve base. (a) is the British four-pin base, and (b) the British five-pin base; (c) is the standard British seven-pin base; (d) is the international octal base; (e) the Mazda octal base, and (f) is the side-contact base.

Cathode Rays

We have already seen that in a hard vacuum, a stream of fast electrons can be produced from a hot cathode, and we know that these can produce fluorescence in certain chemicals and that they travel in straight lines. We know also that they may be deflected and we can judge that, being negatively charged, they will be affected by the charge on any electrode placed near them.

All this knowledge will assist us to understand the basic principles of the new wonder worker of the electrical world, the cathode-ray tube.

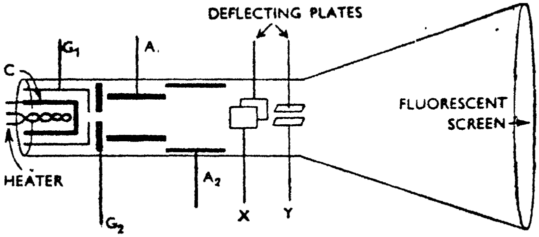


Fig. 14. Purely schematic diagram of a cathode-ray tube. C is the cathode, G_1 and G_2 the grids, A_1 and A_2 the anodes, X and Y the deflecting plates.

A schematic diagram is given in Fig. 14. We can imagine for a moment that all the electrodes are removed except the heater and cathode; then the passage of current through the heater would produce an emission of electrons from the cathode. But the cathode would then be positively charged and so attract the electrons back again. We have already considered this point in connection with our discharge tube and the valve. So we must have an anode which will be positively charged and so attract the electrons.

If this anode is made hollow, many of the fast-moving particles will pass through and reach the fluorescent screen and produce light, which we can see from the outside if the layer of fluorescent material is thin enough.

Such a stream of electrons would spread as a result of their repelling each other. Therefore, the light on the screen would be a fairly large diffused spot. For our especial purpose we need a sharply defined point of light whose movements we can examine.

We must, therefore, provide a means of focusing the beam. We might make the hole through the anode so small that only a very narrow beam would get through, but then the intensity of the light spot would be low. So we must arrange somehow to pile a wide stream together, meeting in a very small spot at the screen. We can do this either by putting electromagnets near the beam (magnetic focusing), or by a cunning arrangement of electrodes with different potentials on them, so devised as to concentrate the electrons at the right place (electrostatic focusing).

Electron Lens

This is the method shown in the illustration, where G_2, A_1, and A_2 are electrodes given positive potentials by an outside supply. They constitute an "electron lens" which focuses the beam.

We also need a means of controlling the intensity of the light spot. This is achieved by a potential on G_1, a metal cylinder surrounding the cathode. If the potential on this "grid" is varied, the intensity of the light spot is varied also, and in proportion to the grid variation.

With all the electrodes already mentioned, if the correct potentials are applied to the parts of the electron lens, we get a sharp spot of light on the screen when the heater supply is switched on. Now we come to the purpose of the two parallel plates marked *X*, and the pair, also parallel, but at right angles to the *X* plates, called *Y* plates. Join the *X* plates in series with a switch and a H.T. battery. Join the *Y* plates in series with another switch and a high-tension battery.

With the switches open, a spot is seen at the centre of the screen. Switch on the *X* circuit; at once the spot is attracted to one side horizontally. Switch off; the spot returns to the centre. Switch on the *Y* circuit; the spot flies either upwards or downwards, according to whether the positive plate is the top one or lower one. Switch off; the spot returns to the centre.

Deflecting Plates

If we next switch on both circuits, the spot flies to a position decided by the relative values of the potentials on the *X* and *Y* plates.

These *X* and *Y* plates, therefore, give us a means of making the light spot move in any direction we wish. They are called *deflecting plates*.

Such is the device illustrated in Fig. 14, though we must not think that the anode and grid arrangements are the only possible ones. But every cathode-ray tube will have an intensity control, a focusing device, and deflection devices, in addition to the cathode emitter and the screen.

Low-current Voltmeter

With the tube thus fitted and the associated circuits for providing potentials, what use can we make of the whole? As it stands, not very much. Once we know the sensitivity, i.e. how many volts are needed on *X* or *Y* plates to deflect the spot one centimetre, we can use it as a voltmeter of very low current consumption.

If we apply an alternating voltage to the *Y* plates, with nothing on the *X* plates, the spot moves up and down and traces out a vertical line. If the frequency of alternation is greater than about 30 c.p.s., we see an apparently fixed vertical line; but at lower frequencies we actually see the spot traversing.

Spread-out Alternations

Now, if at the same time we had the spot also traversing in a horizontal direction, the alternations would be, so to speak, spread out. We can achieve this by means of an accessory circuit connected to the *X* plates.

The simplest of such circuits utilizes the charging up of a condenser connected to the plates. The spot traverses the screen as the p.d. between the two *X* plates increases. The condenser is connected also between grid and cathode of a thyratron and, at the top value of the condenser charge, the valve fires and discharges the condenser very quickly. The spot returns almost instantaneously to its starting point.

Then the valve becomes inactive again and the condenser starts to charge up and the spot starts its horizontal journey once more.

This is only one of several different types of circuit used for making the spot do a periodic horizontal traverse. The expression used is *time base circuit*. A good one will make the spot traverse to the limit of the screen and then fly back to its starting point in such a minute interval of time that we say the fly-back is instantaneous.

The time-base circuit must be controllable so that we can alter both the length of the sweep on the screen and also the frequency of the sweeps. With such a circuit added to a cathode-ray tube, we have an instrument of many uses, known as a *cathode-ray oscillograph.*

Action of Time Base

For example, if we apply an alternating mains voltage to the *Y* plates and adjust the time base so that one sweep is made in the time of one mains alternation, then the successive traces overlay each other and we see an apparently still picture of one complete alternation and can examine it at leisure or photograph it. We can arrange the time base to take in as many alternations as we like, and we get a still picture (i.e. apparently still) whenever the number of mains alternations is exactly a whole number of times the frequency of horizontal traverse.

With such an instrument we can examine visually the detailed nature of any periodic voltage or current. We can look for the weakness in the wave-form from an old alternator, or check the form of an oscillation produced by sound, or measure the frequency of any oscillation (by knowing the time base frequency), and so on.

It is the C.R. tube which has made television an accomplished fact. The received signal is split up into parts. The intensity of light spot part goes to the tube intensity control; the part which controls the vertical sweep goes to the *Y* plates, and the part which goes to the *X* plates is that which controls the horizontal sweep. Then the signal makes the spot cover a whole area by sweeping vertically and horizontally, at the same time altering in intensity. If the whole area is swept too quickly for us to see the separate changes, we see a picture in light and dark corresponding to the scene being televised. Of course, extra apparatus is needed for doing the separation and amplification and for taking the speech part of the signal and sending it through a loudspeaker, but we are here concerned with the C.R. tube alone (Fig. 15).

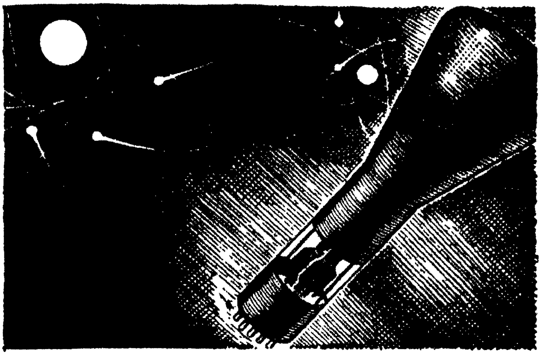


Fig. 15. Electrons evicted from their orbits are made to serve practical purposes in the cathode-ray tube.

Electron Microscope

The electron microscope (Fig. 16) is, basically, a very large cathode-ray tube. As we have learned, a thin beam will spread in its journey along a tube, and so an object if transparent to different degrees can be placed in the path of a beam near the source, and at the fluorescent screen the shadow picture is enormously magnified.

The degree of magnification depends on the dimensions of the

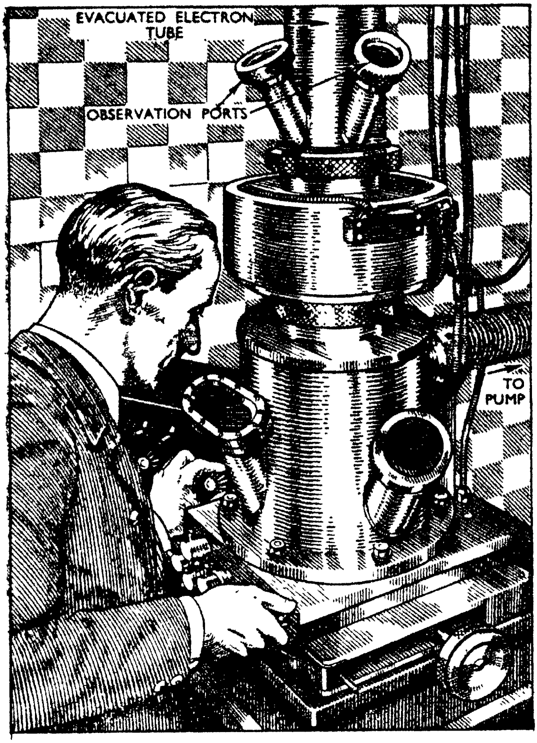


Fig. 16. This electron microscope can give magnifications of as much as 70,000. Basically, it is a very large cathode-ray tube, and is used for laboratory work. Magnification depends on size of tube and focusing.

tube and the system of focusing. Magnetic focusing is used (Fig. 17) and screens are used to cut out the peripheral electrons, and the central ones pass through each such screen and then spread out again. So by the time the electron beam, which was of a width comparable to the object being examined, has arrived at the screen, the spread is very great indeed. The tube is some 6 ft. long and encased in metal, and is mounted vertically.

The objects to be examined must be very thin in order not to absorb the electrons altogether, and as the interior of the tube is a vacuum, the specimen must also be dry. At the moment, the instrument is used for non-living matter and dried bacteria and the like.

An ordinary optical microscope can be used for magnifications up to about 1000 times, but the electron microscope can give a magnification of as much as 70,000. With a figure of 65,000 influenza germs have been made visible for the first time.

Photo-electrons

Another way of interfering with atoms has not yet been considered here. Electrons at high speed will create havoc inside many atoms. That we know. But electrons can be made to fly out from their atoms by the application of light of sufficient intensity. The electrons so emitted are called *photo-electrons*, and the phenomenon is the *photo-electric effect.*

Light-sensitive Material

Some materials are very sensitive to light in this way; for example, potassium and cæsium. To make the effect usable, we mount a plate coated with the light-sensitive material inside an evacuated glass bulb and opposite a loop or a mesh of wire. The two electrodes are brought out to pins, or one to a pin and the other to a top cap, as with

valves. One such is shown in Fig. 18.

If this photo-electric cell is joined in circuit with a battery and an instrument for registering current, so that the loop or mesh is positive with respect to the plate, we have a useful arrangement. If light is shown through the loop or mesh on the plate, electrons are emitted and go to the positive loop and so current flows and is shown on the instrument.

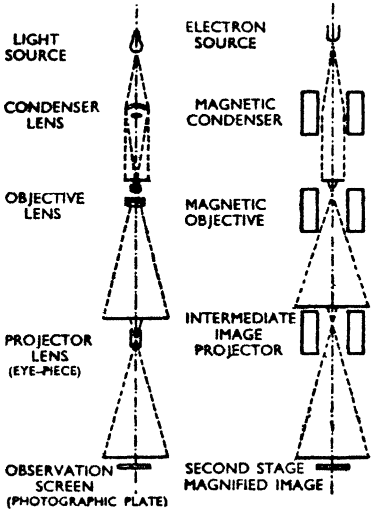
The obvious use of such a cell is to measure the intensity of light by means of electricity. It has been so used, though today there is another type of cell more practicable. But the uses of the photo-electric cell are still very many. It is used as a method of automatic counting; for example, people passing a barrier or sheets of paper passing off a machine, and so on.

The principle of all the counting devices is the The cell and its circuit ined to an ical relay. When light is interrupted, the current suddenly falls and the relay is arranged to trip over and operate a toothed-wheel counter, somewhat similar to a cyclometer.

A popular use of this cell is the automatic switching of interior lighting systems. The cell and battery are arranged with a relay adjusted to trip over for a certain low level of current. When the

conveniently placed, decreases owing to fog or the coming of evening, the photo-electric current

operating a switch. If the outside light should increase again, the


LIGHT SOURCE
CONDENSER LENS
OBJECTIVE LENS
PROJECTOR LENS (EYE-PIECE)
OBSERVATION SCREEN (PHOTOGRAPHIC PLATE)
ELECTRON SOURCE
MAGNETIC CONDENSER
MAGNETIC OBJECTIVE
INTERMEDIATE IMAGE PROJECTOR
SECOND STAGE MAGNIFIED IMAGE

the
[illegible] the
essential features of the electron microscope, on right, from which the similarity can be seen. While the general
[illegible]
in the action of a magnetic lens, which produces a rotation of the image about the axis of the microscope. The final
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similar to the screens used in X-ray work, and which emit a greenish light when the electrons fall upon them.

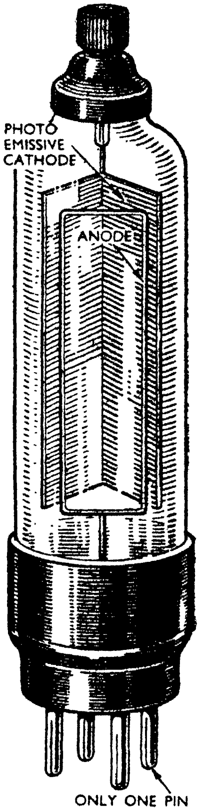


Fig. 18. Photo-electric cell, fitted with standard four-pin valve base.

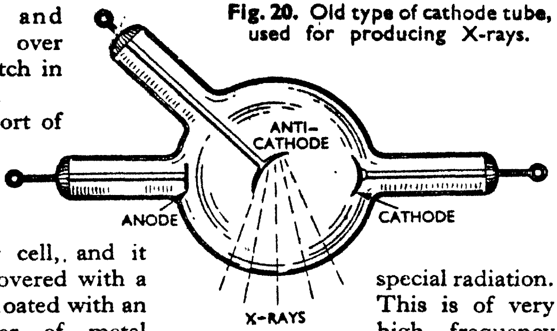


Fig. 20. Old type of cathode tube, used for producing X-rays.

current increases and another relay trips over and operates the switch in the reverse direction.

There is another sort of cell which is not strictly photo-electric but depends for its action on light. It is a *photo-voltaic* cell,. and it consists of a metal covered with a compound and then coated with an extremely thin layer of metal again; this last layer must be transparent.

Light on this layer or film causes the material touching it to become conductive and a current flows in an associated circuit. This current is much greater than for the photo-electric cell and so can be used directly with a micro-ammeter without any amplifying apparatus; moreover, no high-tension supply is needed.

Photo-voltaic cells are used in exposure meters and instruments for measuring illumination. A small instrument of this kind can be carried in the pocket (Fig. 19).

Producing X-rays

Earlier on we said that when fast electrons hit a metal, some of the energy is released in the form of a special radiation. This is of very high frequency indeed, and is known under the popular name of *X-rays*.

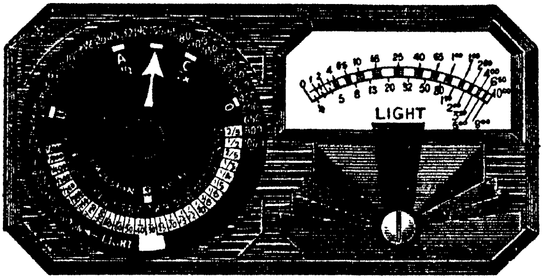


Fig. 19. Incorporated in this Weston photographic exposure meter is a photo-voltaic cell. It is to be found, on the left, under the rotating disk.

This radiation will produce fluorescence just like an electron beam, will ionize gases in a similar way, but cannot be deflected by a magnet and carries no charge.

Great Heat Developed

One way of producing X-rays is shown in the old type of tube illustrated in Fig. 20. The cathode rays bombard the target (the "anti-cathode") on their way to the anode, which they never reach; the X-rays are given off in the direction shown. Today we use tubes containing water-cooled targets (for great heat is caused by electron bombardment, with the consequent deterioration of the tube), with the distance between target and cathode very small, and with a hot cathode.

These rays are very penetrating, and it takes a dense material, such as lead, to stop them. If a fluorescent screen or a photographic plate is placed on the opposite side of an object to an X-ray tube, a shadow picture is produced. The darkness of each part of the picture is proportional to the absorbing power of the material through which the rays pass. So the shadow picture of a hand, for example, shows the flesh very faint, with the bones darker and clearly defined, and any metal adornments as very dark areas.

Soon after the discovery of these rays, scientists realized that here was a method of actually seeing what was happening inside a body. It became a standard practice to take X-ray photographs in order to detect bone injuries, tooth malformations, tumours and abscesses and malignant growths.

Benefits to Mankind

The medical use of X-rays is the most spectacular and interesting to all people. But there are other important uses. They are used to examine crystal structure and have provided evidence of molecular and atomic arrangements inside the crystals. So part of our seemingly fantastic electron theory is due to the evidence provided by X-ray analysis.

They may be used to examine the crystalline structure of metals and so provide evidence of internal cleavages which otherwise might remain unsuspected until the bridge, or crane, or what you will, collapsed after a few years of service, with perhaps tragic results.

Splitting the Atom

We have heard in the popular press a lot about splitting the atoms and what the results might be. Once upon a time it provided a regular six-monthly scare.

What are the facts? We split the atom in everyday life when we use valves or lamps or any electrical device, for electrons are driven out of their orbits. But this is not what is meant by the sensational writers. They refer to the splitting up of the nucleus of an atom, so creating new materials and releasing energy.

Breaking up Nucleus

It is very difficult to tear out the inner orbit electrons from an atom possessing several shells. Enormous energy is required. We can imagine how much more difficult is the task of breaking up the nucleus itself, consisting as it does of parts so closely bound together. Nevertheless, the task has been done. There are materials which are called radio-active, such as radium. These naturally split up all the time, and in the process they give off rapidly moving particles. These are called α-particles (pronounced "alpha") and are known to be positively charged helium atoms, i.e. a nucleus of two positive units and one orbital electron. They are heavier than electrons and move at about 20,000 miles per second. If they are directed into a gas such as nitrogen, the chances are that one particle will hit the nucleus of a nitrogen atom.

This process has been effected and nitrogen nuclei broken up by the impact. Now we know that the character of an element depends on the charge on the nucleus and its weight, together with the number of orbital electrons. If we eject any of these electrons, the substance is ionized but it is still the same substance chemically. Positively charged helium is still helium.

But if the nucleus of an atom is split up, then we have another element entirely. And this happened, for an atom of oxygen and one of hydrogen were produced when an α-particle hit a nitrogen nucleus.

In the course of these researches, very fast projectiles were discovered, not electrons or α-particles, and these have been used for still more effective bombardments of nuclei. The latest device for producing these projectiles is the cyclotron. In this a stream of electrons is accelerated in steps until their energy is such as would necessitate six million volts to produce in normal discharge tubes.

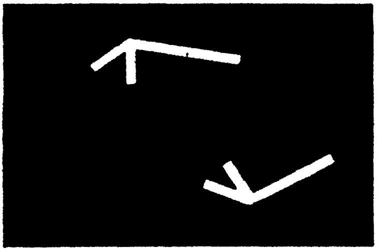


Fig. 21. Indirect evidence of two positively charged helium atoms and a lithium nucleus, formed from each atom of nitrogen split up by the bombardment of neutrons. The white tracks are the illuminated water drops formed along the paths of the three projectiles after the neutron has hit each atom. The path of the neutron is itself invisible, because, being neutral, it produces no ionization as it travels.

Changing Elements

By these bombardments, elements have been changed into one another over the range of all known elements. We have found the philosopher's stone.

The bombardment is like firing a Bren gun into the Albert Hall to hit a fly, but the development of another method has led to the production of the atomic bomb.

It was discovered that atoms of a rare variety of uranium give off neutrons and that when these strike similar uranium atoms, they are not only split but eject still more neutrons. If the sample of uranium is small, the chances of a neutron hitting an atom are remote, but if the sample is above a certain quantity the chances of a hit are increased to a certainty. Once the splitting action starts, the release of neutrons is cumulative and all the atoms in the sample are split.

In conclusion, we may mention one of the very ingenious arrangements which have contributed so much to our knowledge of atomic structure; it is due to C. T. R. Wilson. A sealed compartment, free of all dust, contains air saturated with water vapour. If a particle traverses the air, it produces minute droplets of water along its path and these can be photographed if illuminated.

Deducing Facts

In this way the tracks of α-particles and electrons and so on can be seen, and the use of mathematics in connection with the track lengths and angles enables us to deduce still further facts about the actual particles making the tracks and the nature of the result of a nuclear bombardment. One such picture, showing two bombardments, is given in Fig. 21.

Electronic devices range from radio and television receivers and the later development of radar, to such things as the control of welding machines and the positioning of swing bridges. All these are fairly recent developments, for in no branch of engineering has such great progress been made during the last decade as in electronics.

CHAPTER 15

APPLICATIONS OF ELECTRICITY

EMPLOYMENT IN THE ELECTRICAL INDUSTRY. PRODUCTION AND DESIGN. HIGH-FREQUENCY METHODS OF HEATING. DIELECTRIC HEATING. ELECTRICITY THROUGH LIQUIDS. PLATING. VARIOUS TYPES OF LAMP. LIGHTING BY INVISIBLE RAYS. BROADCASTING. TELEVISION. TALKING FILM. INDUSTRIAL ELECTRONICS. LIGHT-SENSITIVE CELL. USE IN MEDICINE AND SURGERY.

MOST readers of this book have, no doubt, studied it with a view to better qualifying themselves for a successful career in the electrical industry. For those who have not decided on the line of work for which they are best suited, it will be helpful to review, in this chapter, the remarkable scope of this greatest of the new industries and the variety of careers it offers.

Many Careers

Applications of electricity in modern society, and the jobs thereby created, are so numerous that a large volume could be written on these aspects alone. In the space available, we can outline only the main categories of electrical services, motive power, heating, lighting, research and so forth, leaving the reader largely to visualize for himself the sort of career that can be fashioned in each.

Taking a wide view, the beginner in electrical engineering is offered a choice of jobs ranging through generation, distribution, manufacture, installation, and utilization.

Each of these main branches can be divided into sections, each presenting a variety of interesting employments.

Generation, for instance, requires, on the one hand, a man for the actual control and supervision of the giant turbo-alternators and, on the other, a man who, seated before a great panel of meters, lights and switches, may direct the flow of electric power over a large part of Britain.

The former has to see that one machine is always right and ready; the latter has to know just how the public's habits and duties affect the "load" from hour to hour; he has even to take into consideration the weather forecast. He has to bring whole generating stations into action as required and he must be able quickly to plan and bring into being an alternative supply route in the event of failure in any one particular section.

Distribution

The side of the industry concerned with distribution, that is, with getting supply from the generating station (or grid system) to the consumers' premises, is complex and extremely important. The actual provision of supply cables is but one aspect of its work; it is responsible for meeting, and creating, the public demand for electricity; it has to provide and maintain many types of apparatus in the home and factory and on the highways; it has to see that prices are just right.

Essential Organizer

The engineer-manager of a supply authority has to be both a technical expert and a salesman. On his organization he has scores of different grades of worker, from the woman showroom demonstrator, who is an expert in the use of domestic electrical appliances, to the man who works on cable installation; from the man who reads the meter to the man who can advise a big factory on its power problems.

Incidentally, one of the latest cables is only 4·8 in. in diameter but can carry the entire output of a large generating station. It contains three conductors conveying 132 kV and employs a "jacket" of nitrogen gas at a pressure of 200 lb. per sq. in. So you see, the production and use of a "mere cable" can be one of the most remarkable achievements of our times.

Electrical manufacturing ranges from the production and design of cables like this, down to the making of wires finer than a hair; from the fabrication of turbo-alternators to the making of a vacuum-cleaner motor; from the production of oil-filled circuit-breakers down to a bell-push switch; from electric locomotives (Fig. 1) to "gadgets" on cars; from hundreds of types of lamp to telephones, batteries, lifts. The list is well-nigh endless.

In each factory concerned with some particular category of electrical device, there are many jobs for trained men, from that of

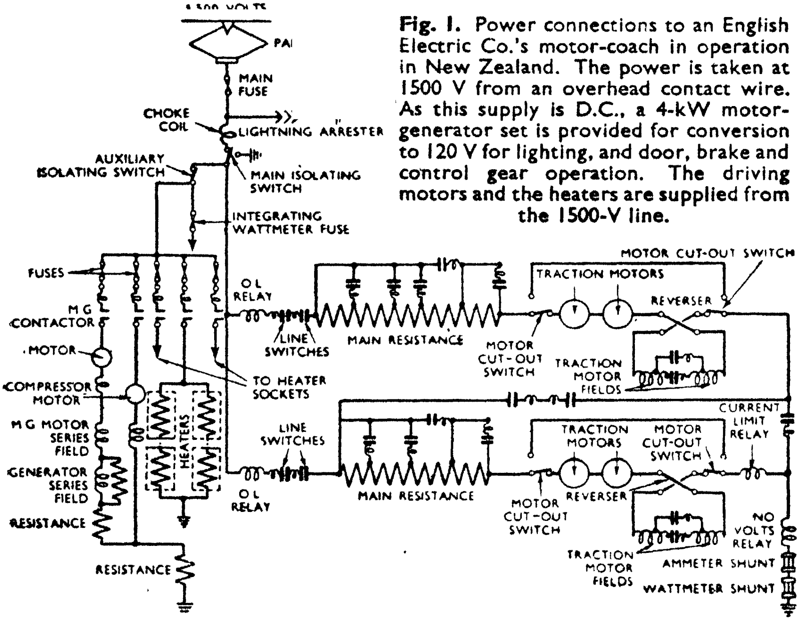


Fig. 1. Power connections to an English Electric Co.'s motor-coach in operation in New Zealand. The power is taken at 1500 V from an overhead contact wire. As this supply is D.C., a 4-kW motor-generator set is provided for conversion to 120 V for lighting, and door, brake and control gear operation. The driving motors and the heaters are supplied from the 1500-V line.

production line supervisor to that of research engineer.

Installation and utilization comprise a vast field in which wiremen, lighting engineers, heating and refrigeration engineers and other specialists have their places. But, as we have indicated, it will be more helpful in the present instance to review some of the main applications of electricity rather than to go on listing kinds of job.

Just one further word, however, of general advice. Like his counterpart in other engineering professions, the electrical man must have some natural engineering bent. Actual electrical work is mostly of a mechanical nature, the main distinction lying, not in what the worker does, but in what he knows.

A man installing electric motors in a factory would not get far if he did not understand the behaviour of that invisible "juice," electricity; on the other hand, he would be equally useless unless he knew how to make a sound mechanical job of the wiring, switching, control panels and so on.

Even in the higher branches of the science, design and research, a considerable knowledge of mechanics and physical design is necessary. There is a lot in the remark that good engineers "think with their hands."

The beginner cannot be advised too strongly to get himself a good grounding in mathematics and algebra so that he can, at the least, appreciate vector diagrams, phase differences, R.M.S. values, and can carry out power and Ohm's Law calculations for both D.C. and A.C. circuits.

The young man should attend evening or day classes regularly. Once he has mastered the fundamental principles and acquired a general idea of the electrical industry he should specialize, and not attempt to cover too much.

Fortunately, many of the larger manufacturing firms now have apprentice training schemes in which theoretical and practical training march side by side. Education authorities, generally, are showing awareness of the need for closer contact between workshop and classroom.

Power Conveyance

Now to look at some of the applications of electricity. First, electricity as a source of power, or, to be exact, as a conveyer of power. The actual source is the fuel burnt at the power station, and the electrical circuits correspond to a shaft-and-pulley system for applying the power to the remote points at which it is needed.

A great advantage of electricity, possibly its greatest, is that this remarkable "shaft-and-pulley" system can be extended scores of miles and can be introduced into either factory or home with equal ease. For instance, by running a few yards of wire into a house we can make available 5 h.p. or more in the kitchen for cooking and a fraction of a horse-power wherever needed for lighting and for vacuum cleaning.

In the road outside, a trolley-bus or tram may be taking 50 h.p. or so from the same supply. Across the road, some machine or process may be taking several hundred h.p.

It is unusual, perhaps, to talk of horse-power in this way in connection with electricity, but it is occasionally helpful to do so because many of us have a better

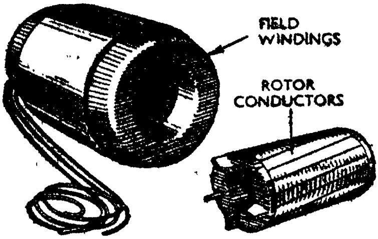


Fig. 2. Stator (left) and rotor (right) of motor designed for building into the machine to be driven.

idea of what a horse-power means than of what 746 electrical watts amount to.

Actually, 746 W are equal to 1 h.p., and 1 h.p. can raise 33,000 lb. one foot in one minute. A "unit" is 1000 W (1 kW) employed for one hour and, therefore, by human standards represents a considerable amount of work.

It has been calculated that a horse-power is 7½ times as great as one "man-power," and a kilowatt is, therefore, equal to ten men. In practice, a man cannot work even at this rate for any length of time and it is reckoned that in a ten-hour day a third of a "unit" (330 watt-hours) is all the work a man can do.

Electricity, however, has to supplant not only human power but also that produced by efficient steam and internal-combustion engines. It is doing so on grounds other than cost, chiefly those of adaptability and simplicity of control, especially by automatic means.

A factory used to be a place of humming belts driving many different machines, but in these days driving belts are rarely seen. More often, small electric motors are built into the machines and become an integral part of them. With the development of the three-phase motor, one of the simplest power sources ever devised, this "building-in" presents no difficulties. Fig. 2 shows the component parts of such a motor.

The smaller part, the rotor, is bored and fitted with a keyway to take the machine shaft, and forms a practically indestructible assembly.

In Fig. 3 is seen a spindle moulding machine with two built-in motors. It will be noted that the operator is not faced with whirring shafts and flapping belts.

Electrically Driven Tools

Electric power has been fitted to many hand tools, grinders, polishers, drills, and even screw-drivers. This permits a great volume of output without undue fatigue for the worker. Three of these portable machines are seen in Fig. 4.

The applications of electric welding are now so numerous and so easily carried out that it is usual to entrust a great deal of this work to

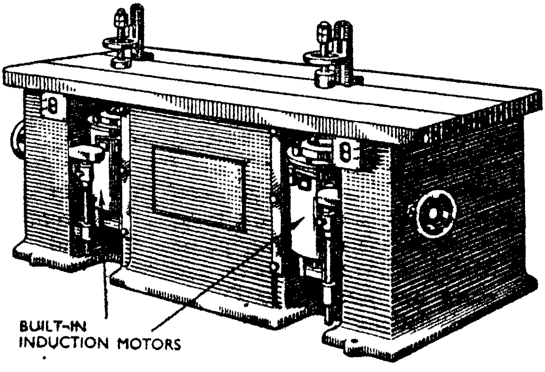
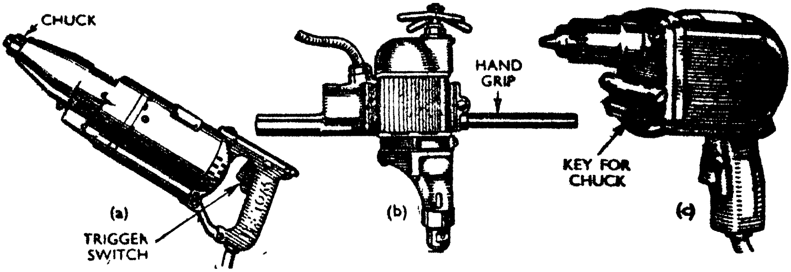


Fig. 3. Sagar double-spindle moulding machine, driven by two built-in English Electric motors.



EXAMPLES OF PORTABLE ELECTRICALLY DRIVEN TOOLS

Fig. 4. Portable power tools which are widely used include: (a) ¼-in. lightweight drill. (b) 1¼-in. drill. (c) Screw-driver or nutsetter with clutch and reverse plug.

women and girls (Fig. 5). Another labour-saving electrical application that can be noted in the modern factory is the small battery-driven crane and truck (Fig. 6), which enables a girl to lift, for example an aeroplane engine, speedily convey it to another department, and unload it exactly

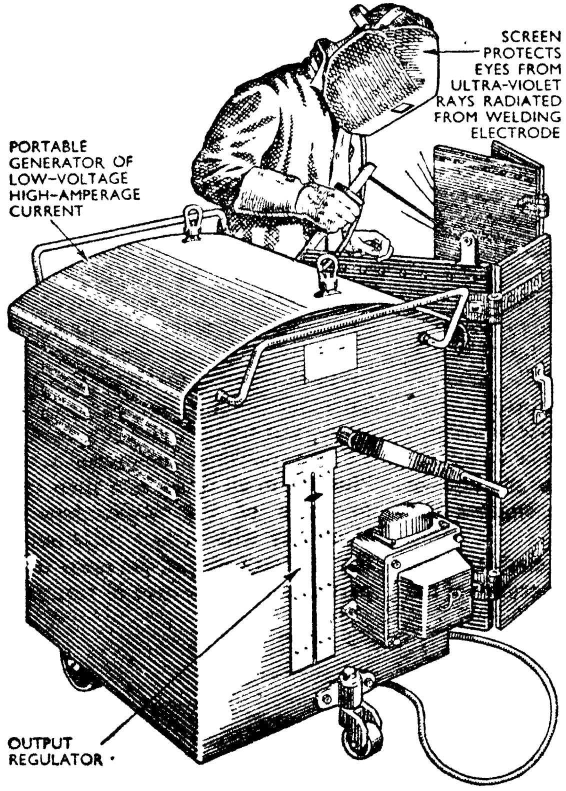

SCREEN PROTECTS EYES FROM ULTRA-VIOLET RAYS RADIATED FROM WELDING ELECTRODE
PORTABLE GENERATOR OF LOW-VOLTAGE HIGH-AMPERAGE CURRENT
OUTPUT REGULATOR

Fig. 5. Modern electric welding apparatus which is transportable and can be operated by female labour.

addition to machines common to many industries, there are numerous ways in which electricity serves the special needs of particular trades. For example, our coal mines are becoming highly mechanized (Fig. 7), electrical machinery cutting the coal, conveying it to the skips, raising it to the surface and "screening" it before final transportation.

The great car and aeroplane industries depend very considerably

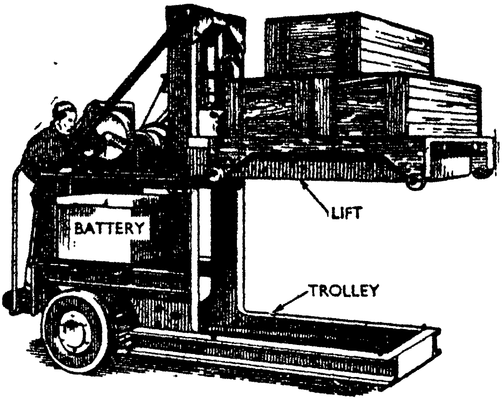


Fig. 6. Another electrical application in the modern factory is the battery-driven crane or truck.

on electricity. Without electric ignition the commercial and technical development of the internal combustion engine would have been much slower. A battery-driven electric vehicle is illustrated in Fig. 8. And imagine winter motoring without an electric starter and electric headlights (Fig. 9).

Electrical Traction

Electric trains are replacing the steam locomotive; the underground train, the tram and trolley-bus are electric. Electricity provides well-nigh indispensable services on ships of all sizes. There is a trend towards its use as the method of transmission between engines and screws in large ships.

Electric ignition enabled the first aeroplanes to fly because of the power-weight ratio of the engine. It is still used in the great majority of aero engines. But in a modern aeroplane there are dozens of applications of electricity, from adjusting the propeller speed and angle to melting ice off the wing edges, from heating the airman's flying suit to raising the wheels, from controlling the elevators to direction-finding and "blind" landing.

The cinema depends on electricity; no other form of lighting could produce the intense, concentrated source needed for the projection, or even the brilliance for filming in the studio.

Electroplating is a new industry built entirely by electricity and, in turn, contributing enormously to other trades. For instance, an important printing process employs great etched rollers given a hard-wearing surface by electroplating.

Aluminium and other "modern" metals are produced by the use of vast quantities of electric power; electrical processes are vital to the production of many chemicals.

But we could go from industry to industry in this way and the catalogue might become wearisome. Let us look at a few uses of electric power which are nearer "home" to all of us, and then turn to some of the applications of electricity which are a little out of the ordinary and, at the same time, particularly suggestive of futuristic

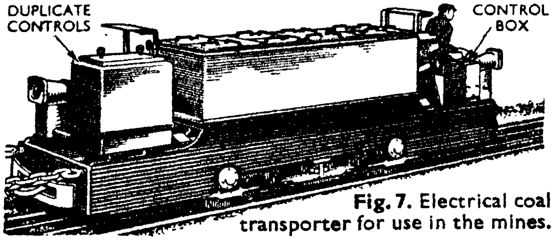
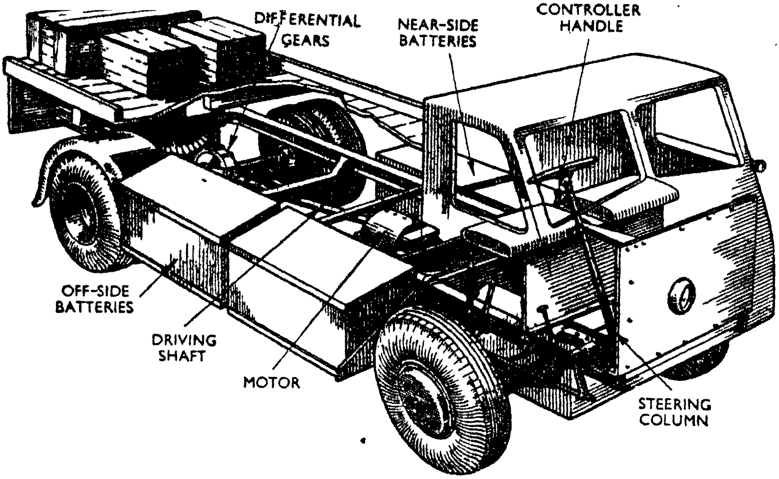


Fig. 7. Electrical coal transporter for use in the mines.



BATTERY-DRIVEN VEHICLE

Fig. 8. Chassis view of an electric vehicle, showing the control gear and position of batteries and motor. Essentially, the electric vehicle consists of a chassis of similar design to that employed on petrol vehicles, but the engine and gear-box are replaced by an electric motor and controller drawing power in the form of electrical energy from the battery, the latter, in a sense, representing the petrol tank.

developments.

In the kitchen, electricity often does the cooking, heats the water in thermostatically controlled storage tanks (Fig. 10), boils the water in a kettle and heats the "automatic" iron. It can do even more, and in future homes we shall see wide use of the washing machine (Fig. 11) and refrigerator (Fig. 12), as well as such items as the fruit juice extractor, toaster (Fig. 13) and waffle iron.

Larger kitchens

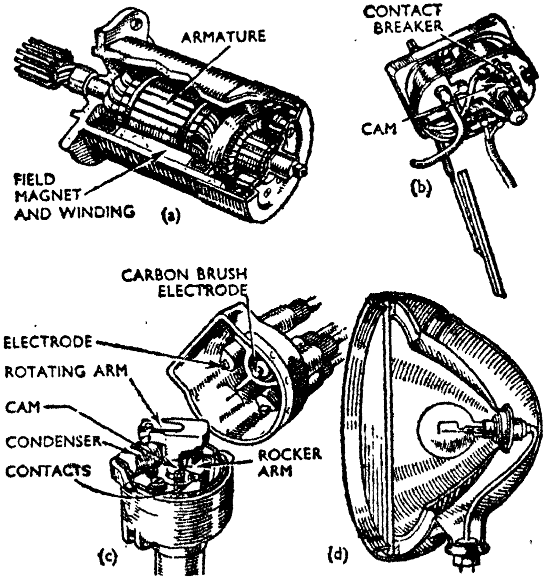


Fig. 9. (a) Sectional view of a motor-car starter motor. (b) Electric windscreen wiper. (c) The distributor which conveys the high-tension current to each sparking plug in turn. (d) Motor-car headlamp.

for canteens and hotels employ potato peelers, cake mixers and perhaps coffee grinders (Fig. 14), in addition to the more familiar apparatus. The refrigerator in its large "commercial" form is of the greatest importance to the catering and food trades. It is used, on the one hand, to make ice cream and, on the other, to bring great shiploads of meat in good condition half-way round the world.

Air-conditioning

Ventilation is a new science or industry which has grown from the simple little electric fan. First, large fans appeared in factories and then extractor·systems, fans connected to large ducts spread throughout a building, came along. Now we have air-conditioning; electricity not only makes a flow of fresh air, but it heats or cools it, adjusts the humidity and, sometimes, exterminates any germs that happen to be in it.

It is said that some of the very big air-conditioned buildings in America have such a delightful "climate" that workers are reluctant to leave at night!

For the country house, water

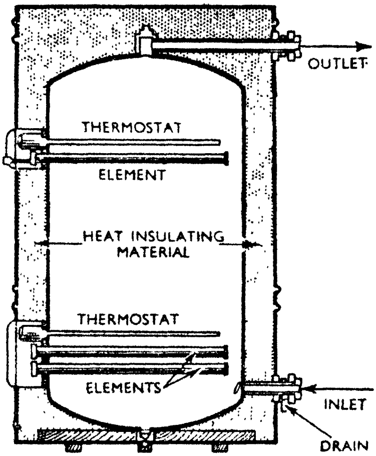


Fig. 10. Section of a modern electrical water-heater. The heating elements consist of spirals of resistance wire enclosed within watertight covers which project into the water. For this reason, they are known as immersion heaters. The elements are arranged in two sections for quick heating of the water. The purpose of the thermostats is to switch the power off when the temperature of the water reaches a certain point, and to switch the power on when the temperature drops. Thus, a constant and economical supply of hot water is available.

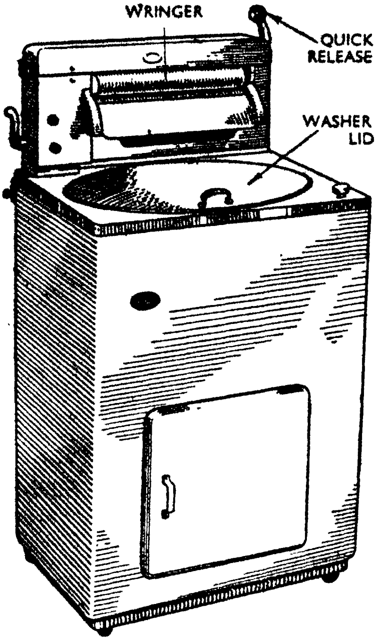
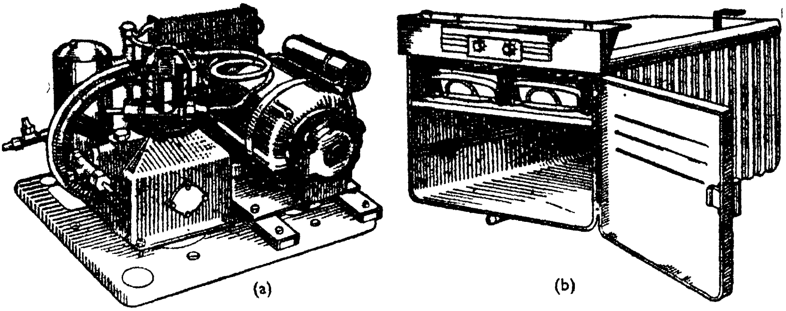


Fig. 11. Domestic washing machine which operates by electricity. The wringer that is attached to it is driven by a fractional horse-power electrical motor. An electrically driven agitator does the washing and, in some models, ordinary resistance heating elements raise the temperature in the boiler. In other types of washer, the water is forced under pressure through the fabrics it is desired to clean.

pumping represents considerable labour if it has to be carried out by hand, but the small automatic electrically driven pump, controlled by means of a float switch in the storage tank, eliminates this hard work and ensures a steady supply of water with great reliability.

A bacon slicer, now a familiar sight in most large shops and restaurants, can be adapted to domestic use, and many a lad now applies the electric motor to his fretsaw.



DOMESTIC TYPE OF ELECTRIC REFRIGERATOR

Fig. 12. The two sections of a domestic refrigerator. (a) Thermostatically controlled condensing unit comprising an electric motor coupled to a compressor, and (b) the evaporator, of electro-tinned copper with chromium-plated door.

So far we have been thinking mostly of power applications. Heating is, of course, a use of power and we could cite many instances where electric radiators, convectors and unit heaters (Fig. 15) are peculiarly suitable for this purpose. To widen our horizons, however, let us consider some of the less usual applications in this connection.

Resistance Heating

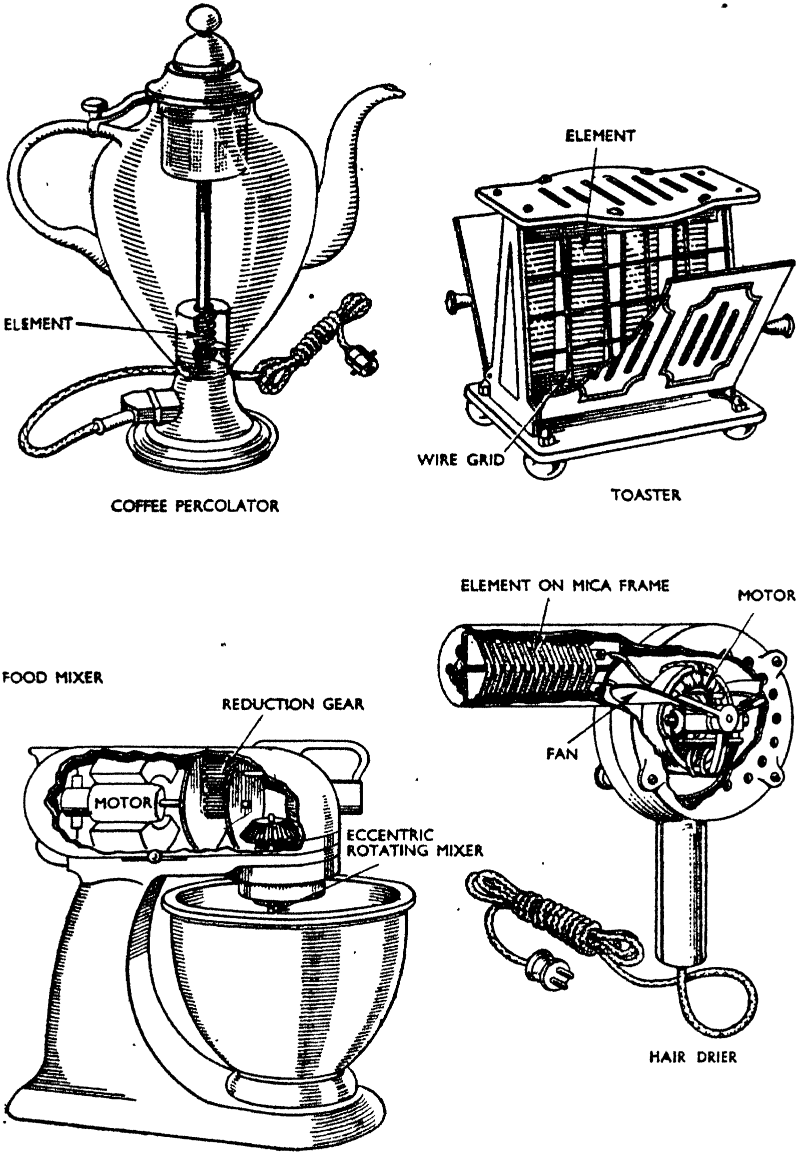
The radiator, the cooker hotplate and the electric kettle derive heat from the passage of current through resistance wires. The electrical engineer has, however, devised other methods of heating, some of which have revolutionized the industries into which they have been introduced.

Induction Furnace

For the manufacture of steel, furnaces have been developed in which there are neither carbon electrodes nor wires heated to incandescence. The high-frequency induction furnace, in fact, puts to good use the eddy currents so detrimental in other machines.

It will be remembered that with transformers, dynamos and motors the designer seeks to eliminate eddy currents. In the induction furnace, effort is made to encourage them.

We know that if primary and secondary windings be placed upon an iron core, an alternating current through the primary induces current in the secondary. The wattage, or power, of these two currents is nearly equal. Although the primary may carry a small current at high voltage, the secondary may carry a very heavy current at a low voltage. A short, thick secondary will contain such a current and, if the conductor is short-circuited, the



ELECTRICALLY OPERATED DOMESTIC APPLIANCES

Fig. 13. Heating effect of electricity is employed in many domestic appliances which are to be found in the modern home, and in other devices small electric motors are used for the production of mechanical power. In some, both of these methods are to be found. The hair drier is an example. A heating element raises the temperature of the air and a motor drives a fan that blows out the heated air.

current may burn the winding out.

In the high-frequency electric furnace, the primary of the "transformer" exists as a winding round the crucible. The secondary current is induced in the material itself and the resulting heavy eddy currents set up such a high temperature that the "charge" melts.

The term "high-frequency," as applied to electric furnaces, usually indicates between 500 and 2500 c.p.s., which is quite "low-frequency" to radio engineers.

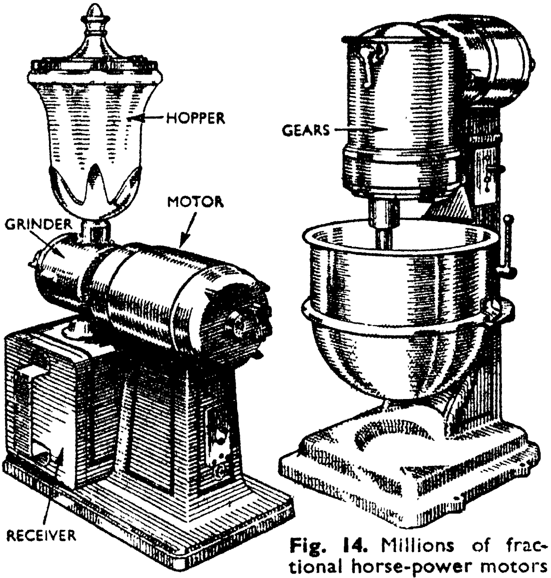


Fig. 14. Millions of fractional horse-power motors are used for such appliances as the Peerless coffee grinder and the Peerless cake mixer illustrated above.

One of the great advantages of the induction furnace is the fact that the interaction of the magnetic field and the eddy currents in the metal charge sets up a violent stirring which results in thorough mixing and produces high-quality alloys attainable by no other means.

A simplified diagram of the induction furnace arrangement is shown in Fig. 16.

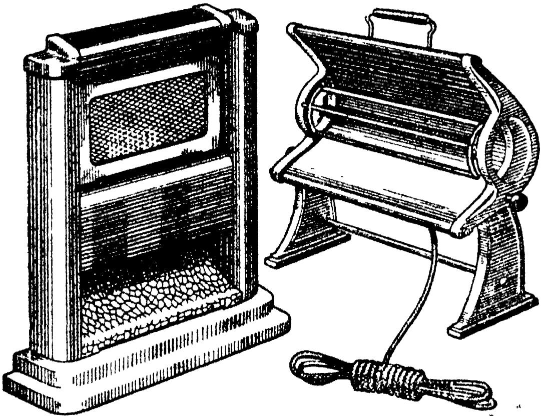


Fig. 15. Two types of electric fire. On the left is an air convector from which heated air is projected through the grille. On the right is a reflector type from which warmth is projected as radiant heat rays.

External Heat

In ordinary methods of heating for industrial purposes, the outside of an object is always hotter than the inside. In the case of materials that have a low thermal conductivity, for instance, many of the plastic substances, this may

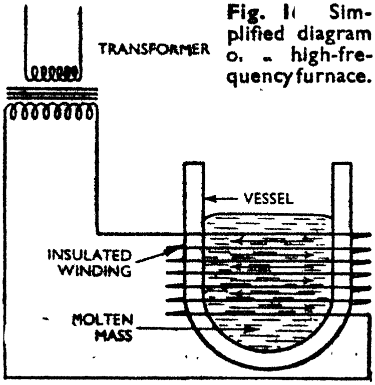


Fig. 16. Simplified diagram of a high-frequency furnace.

mean that to provide sufficient heat at the centre an almost destructive temperature must be applied to the outside.

Electricity has again come to the rescue with what is known as dielectric heating. In this, the molecules constituting the material are set in violent motion and thus made to produce heat. Whatever the defect may be, any material within the sphere of influence has its molecules thrown about with such rapidity that collisions are frequent, and heating takes place.

By this means one end of a nail can be made red hot whilst the other end is held in the unprotected hand; heat may be made to start at the inside of a mass of material simultaneously with the outside.

Let us look at the very simple principles underlying this remarkable process. We know that when an alternating voltage is applied to the plates of a condenser, current appears to travel through the condenser. Actually, the electrons comprising the current do not pass through the dielectric between the plates, but "waves" of energy do so instead.

By the use of very high frequencies (some millions of cycles per second) the dielectric is made to convey so much energy that it becomes very hot, due to losses in the material. The amount of energy released as heat depends upon the "power factor" of the dielectric.

If two electrodes are provided, almost any kind of material may be placed between them to provide a sort of dielectric. Depending upon its power factor and the frequency of the current alternations, heat will be induced in it.

Special Frequency

An ideal arrangement would be to provide a special frequency to suit the particular material to be

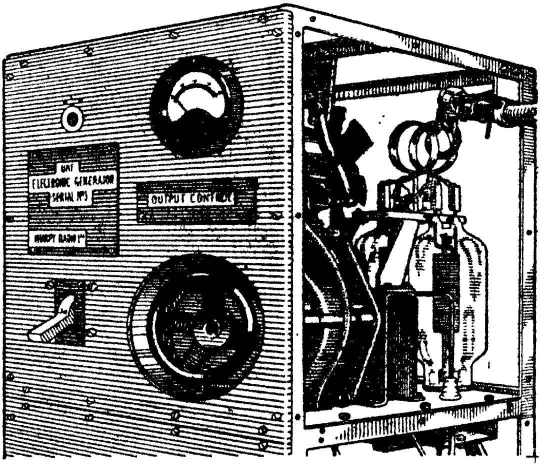


Fig. 17. Generator employed for high-frequency heat treatment of metals and dielectrics. In principle, the apparatus is similar to that part of an ordinary wireless transmitter which generates H.F. oscillations.

heated, but this must be balanced against other practical requirements. The power required may vary between 100 W and 500 kW, and a valve oscillator (Fig. 17), basically similar to a radio transmitter, is employed.

A random selection of uses to which dielectric heating has been put include the drying of tobacco, without removing it from the hogshead in which it is stored; killing weevils in grain (apparently the insects have a higher power factor than the grain, being burnt up whilst the grain remains unaffected); drying glue in plywood; and polymerizing the synthetic resin in resin-bonded wood propellers for aircraft—in this case the two electrodes were shaped to accommodate the propeller contour.

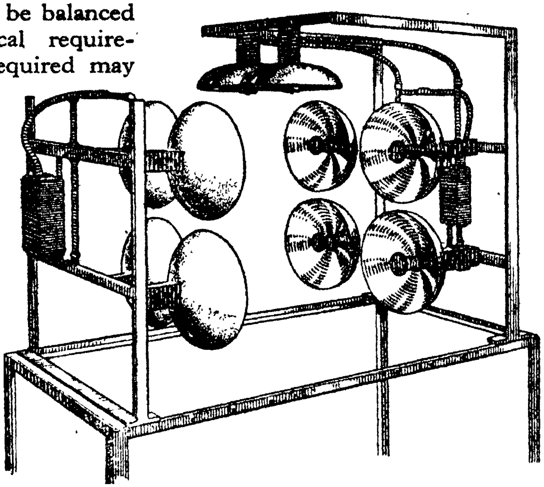


Fig. 18. Equipment for infra-red heating. An open-type assembly showing the unit construction. Wiring is totally enclosed and reflectors can be removed from the front.

Dielectric heating is being applied to the moulding of plastic materials, particularly of the thermosetting type. There is an "electronic sewing-machine" in which the edges of plastic materials can be joined. Two wheels, one above and one below, form the electrodes, or plates, of the condenser, and provide sufficient pressure to unite the two surfaces as they become heated.

Infra-red Heating

There is still another form of electric heating that deserves mention, and this is the drying of paint and varnish by what is known as infra-red heating. Tungsten filament lamps, or special dull-emitter or "black-heat" elements, are the source of heat.

Considerable energy can be radiated by these lamps or elements and the heat is applied to the paint without warming the intervening air. Lamps may be 1000-W types if necessary, and the temperatures reached may be between 1000-1200 deg. absolute. With the dull-emitter types all that is seen is a dull red light, without any unpleasant effects. A simple open-type assembly is illustrated in Fig. 18.

At one time it was thought that the rapid drying of paints and varnishes by this means was due to a catalytic effect, but it is now known that the only way infra-red drys paints is by causing the film and its support to rise in temperature. This rise is due to the absorption of the rays.

We have now begun to appreciate that electricity can be put to work in unexpected ways, so let us now look at some of its chemical effects and the uses made of them.

If a direct current of electricity be passed through a liquid, the phenomenon known as electrolysis takes place, and this results in the liquid being divided up into its components. In the case of water, for instance, oxygen appears at the anode, or the point at which the current enters the water, and hydrogen at the cathode, or point where the current leaves the liquid.

In time, the whole of the water comprising the electrolyte, as it is called, is gone, having been decomposed into its constituent gases.

Storage Battery

This phenomenon is made use of in the electric storage battery, or accumulator, in which two plates of lead sulphate are converted into lead oxide, the positive plate, and pure lead, the negative plate, purely by the action of the released gases. Contrary to popular imagination, an accumulator does not store electricity, but merely converts electrical energy into chemical energy.

When the process of charging is complete, the battery consists of two plates, one of lead oxide and one of lead, and between them an e.m.f. of approximately 2 V exists. During discharge, the plates revert to their original chemical state, and, therefore, the further recharging process becomes necessary.

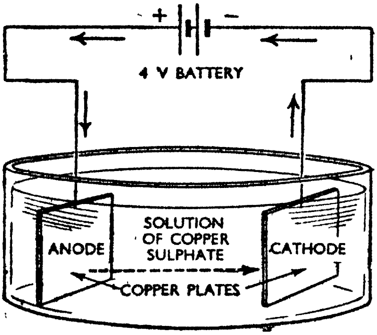


Fig. 19. Simple form of apparatus for demonstrating electrolytic action.

Electroplating

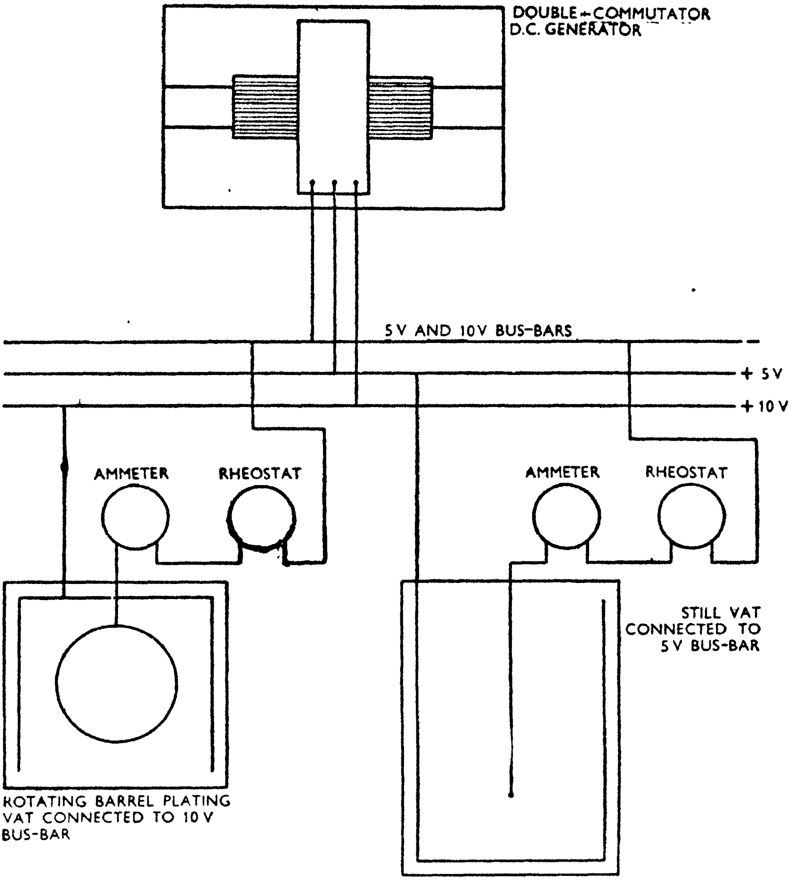
Electrolysis is utilized for many other purposes, one of which is the deposition of metals, or electroplating, as it is called. The process is in itself very simple, and most schoolboys have at some time or another constructed the elementary equipment that enables them to carry out a crude form of electroplating.

In Fig. 19 this simple apparatus is shown, and it will be seen that it consists of a glass vessel containing a solution of copper sulphate, in which two copper electrodes are immersed.

If a D.C. be passed from anode to cathode, the electrolytic action at once commences; assuming that the current enters the anode, and oxygen, from the water making up the solution, appears at this plate. At the same time, hydrogen appears at the cathode, and as there is twice as much hydrogen as oxygen in the constitution of water, the bubbles of gas at the cathode are normally about twice the volume of those at the anode.

Another very interesting phenomenon takes place at the same time. The anode becomes gradually reduced in size and weight, whilst the cathode increases at an equal rate.

In time, the anode completely disappears, and the whole of the metal from it is deposited upon the cathode. Except for the loss of water due to electrolysis, the liquid


DOUBLE-COMMUTATOR D.C. GENERATOR
5 V AND 10 V BUS-BARS
−
+ 5 V
+ 10 V
AMMETER
RHEOSTAT
AMMETER
RHEOSTAT
STILL VAT CONNECTED TO 5 V BUS-BAR
ROTATING BARREL PLATING VAT CONNECTED TO 10 V BUS-BAR

ELECTRICAL SUPPLY FOR A PLATING SHOP

Fig. 20. Supply is at 5 V and 10 V using three-wire distribution from a double-commutator D.C. generator. The current that flows through the vats is controlled.

remains unchanged, or almost so.

Now this rate of copper deposition on the cathode follows very rigid rules, and is in direct proportion to the amount of current flowing. Very briefly, a current of 10 A per sq. ft. of anode will deposit about 12 grammes of copper on the cathode, and will, of course, rob the anode to the same extent. In practice, copper cathode is replaced by an iron or steel object which it is desired to plate with copper, and thus an elementary plating bath is obtained.

It will be obvious that with the use of suitable solutions and anodes, practically any metal may be deposited upon another metal, and silver plating, gold plating and, more commonly, zinc plating on iron or steel for protective purposes, becomes possible. By coating them with various materials, blacklead or metal powders, for instance, even *non*-metallic substances may be electro-plated, but it is obvious that they must first be made electrically conductive by means of these special coatings.

The solutions used for electroplating are highly conductive. Therefore, electric generators of low voltage, but high current output, are required; one such generator is illustrated in the chapter dealing with generators.

Regulated Current

The current through the plating bath must be very carefully regulated. The heavier the current the quicker the deposit of metal on the cathode, but no suspicion of free gas must appear, or the deposit will be porous. A diagram of the usual layout of a plating shop, with the necessary equipment, is given in Fig. 20.

The plater knows the amount of metal that can be deposited per ampere-hour, and he regulates his current flow accordingly. If the plated object has to be polished, then he must, of course, allow for a thicker coating, as some will be removed during the polishing process. This finishing is usually done by means of grinders or high-speed polishing bobs, depending upon the hardness of the deposited metal or the degree of finish required.

Small articles are usually plated in bulk by means of a barrel vat, and this is continuously rotated, carrying out a certain amount of polishing at the same time as plating.

Higher voltages, up to 10 V, are used for barrel plating vats, but the still vat usually requires from 3 to 5 V only. On the other hand, currents up to 200 A are common in large multiple vats, and the methods of conveying such heavy currents at low voltages to the vats and controlling equipment require careful consideration if loss of energy is to be avoided.

The problems of plating are primarily for the chemist, although the electrical engineer must play his part. For instance, the solution for plating zinc on to ferrous metals is made up as follows:

Zinc fluosilicate, 20 ozs.
Aluminium fluosilicate, 17 ozs.
Ammonium fluoride, 8½ ozs.
Gelatine, 0·05 per cent.
Water, 1 gallon.

The work is also immersed in zinc sulphate, or even used as an anode in that solution, in order to improve adherence of the zinc, from which it will be clear that the process is of considerable complexity. For chromium plating, now very popular, the whole plating shop must be laid out under expert supervision.

Plating Bath

In the simple plating bath shown in Fig. 19 it has been found that the purity of the copper deposited on the cathode is very high. This has led to copper refining on a commercial scale, and a great deal of copper is at present electrolytically treated. In this process large vats are filled with copper sulphate solution, and copper anode and cathode plates, up to fifty pairs of plates per vat, are immersed in this solution, with a weight up to three tons.

In some cases, all the anodes and cathodes are connected in parallel, and the individual vats then connected in series; or a variation may be made, and the anodes and cathodes connected in series in the same vat, and thus the intermediate electrodes form both anodes and cathodes, receiving copper on one side and passing it on from the other side.

If the parallel connection is adopted, the low internal resistance of the vat makes necessary a very low voltage between the anodes and cathodes, sometimes no more than 0·2 V.

The actual watt-hours required per kilogramme of copper varies considerably, depending upon conditions, but is usually taken at about 500. At Great Falls, one of the largest works, the voltage per tank is 0·5 V, the current efficiency about 89 per cent, and the watt-hours per kilogramme of copper about 550. The current density is very important, as, if too high, the copper does not adhere.

Silver, gold, and aluminium refining is carried out in a similar manner, and zinc is extracted from ore by means of electrolysis. In the Hoepfner process the roasted zinc ore is leached with a solution of calcium chloride and carbon dioxide; calcium carbonate is thus precipitated, and a solution of zinc chloride obtained; it is this solution which is subjected to electrolysis.

There are many other commercial applications of the electrolytic process, which has now entered into widely differing uses in industry, of which only the more interesting can be mentioned.

One is the purification of sewage by what is known as the Hermite process, and which uses electrolysed sea-water. The galvanizing of iron by the Cowper-Coles method depends upon electrolysis, and it is also used in the production of white lead. Tin is recovered from scrap, nickel is refined, copper tubes are manufactured direct, and leather is tanned, all by means of electrolysis.

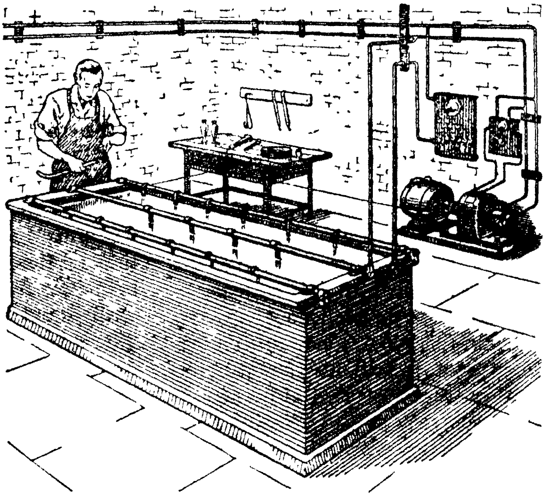


Fig. 21. Layout of a small plating shop. On the right is a motor-generator for reducing the voltage of the mains supply to that necessary for plating, and at the same time providing the heavy currents necessary. Above the generator are starting equipment and shunt regulator; also series resistance and ammeter.

These processes represent the greatest present-day utilization of direct current, for which it is essential. If alternating currents were used the processes would, of course, suffer reversal with the current alternations, and at the end of the day a great deal of current would have been consumed, but no useful work would have been done.

Where only A.C. is available, some form of conversion of direct current is necessary, usually by means of rectifiers or motor-generators, the latter consisting of a low-voltage dynamo driven by means of an A.C. motor.

The layout of a small electroplating shop is drawn in Fig. 21 and comprises a motor-generator, with controls as described, heavy section conductors and one still plating vat.

Electric Lighting

Lighting was the first commercial application of electricity and this chapter would be seriously incomplete without a reference to this incalculably helpful use.

Following the introduction of the gas-filled lamp into this country in 1918, little development in the lighting field took place until a few years ago. It will be remembered that in place of the old vacuum bulb, the new lamp utilized a bulb filled with argon gas, enabling much higher filament temperatures to be reached without undue disintegration of the metal filament.

Of recent years, all lamps intended for miners' use have been filled with krypton, a very heavy inert gas forming about one-millionth part of the atmosphere, as this has a lower heat conductivity than argon.

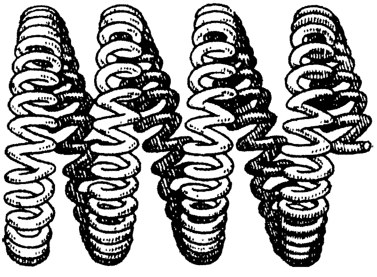


Fig. 22. Coiling of an already coiled filament upon itself; the principle of construction in a coiled-coil lamp.

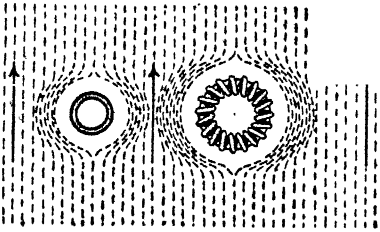


Fig. 23. Although the larger diameter of filament is exposed to the cooling effect of the inert gas, yet its length is so reduced by double coiling that the total effect is also reduced.

Under constant research with a view to obtaining more light for a given current consumption, what was known as the coiled-coil lamp was introduced, and this construction of the filament enabled equal brilliance for a lower consumption, with equal average length of life. The principle of the old incandescent filament was kept, but after being coiled the filament was again coiled upon itself, as shown in Fig. 22.

The total filament surface exposed to the inert gas surrounding it is reduced, and thus less current is required to maintain its brilliance. Approximately 20 per cent more light is possible with this type of filament for any given current consumption.

Filament Diameters

In Fig. 23 the relative diameters of the ordinary coiled filament and the coiled-coil filament with the surrounding gas layers are shown to scale. It might be thought that the larger diameter of the coiled-coil filament would make for increased heat losses, but the sectional diagram cannot, of course, indicate the reduction of filament length, which more than compensates for the increased diameter.

With the perfection of the coiled-coil gas-filled lamp the maximum possibilities of the metal filament lamp appeared to have been reached and research workers turned their attentions. towards a filamentless lamp. Some of the old vacuum tubes used with early induction coils had been filled with neon gas, and the result was a pinkish glow when the current was passed through them; this principle, which is explained in Chapter 14, was utilized in the first lamp made without filaments.

This was known as the neon lamp, which has a very low light output, and it is now mainly used as an indicator lamp, the absence of any filament making it less liable to failure.

"Beehive" Lamp

For dim lighting there is a "beehive" neon lamp with a bulb like that of the ordinary lamp. One electrode is a metal disk and the other a wire spiral looking rather like a beehive. At about 200 volts the lamp "strikes" and a pink glow appears.

Other neon lamps are small glass tubes containing two metal rods. These are used in simple voltage and spark-plug testers. The current passed is so minute that it can jump across a small capacity and so direct connections are not always necessary.

Between 1920 and 1930 some considerable use was made of a lamp in which an arc was drawn between an iron electrode and a pool of mercury, contained within a glass tube. Mercury vapour gas was formed in the tube, which was conductive, and the current flow was maintained through this with a resulting greenish-blue light output.

Although unpleasant for general use, the light was highly actinic, which made it extremely useful for photographic purposes; it found general adoption in cinema film studios, and for similar uses.

In 1932 a great improvement upon this lamp was introduced in this country, and in which mercury vapour was sealed under high pressure in a glass tube. Two electrodes were introduced into this tube, and when these were connected to an A.C. supply above 200 V, it was found that the characteristic greenish-blue glow was readily produced. The modern lamp makes use of a mixture of gases, in which mercury vapour predominates and the light is produced not because the gas or vapour is raised to a high temperature, but by the passage of electricity through this mixture of gases at a higher pressure than was formerly practicable.

The high-pressure mercury vapour lamp gives three times as much light as an ordinary gas-filled tungsten filament lamp of equal wattage, but requires the use of certain accessories. For instance, a mercury vapour lamp has no stable resistance, in the ordinary sense of the word, and a choke coil must always, of course, be used with it.

This has the effect of seriously reducing the power factor of the lamp, and a condenser must be installed to correct this to some extent. In addition, interference with radio reception is possible with these lamps, and this again may need additional equipment for correction.

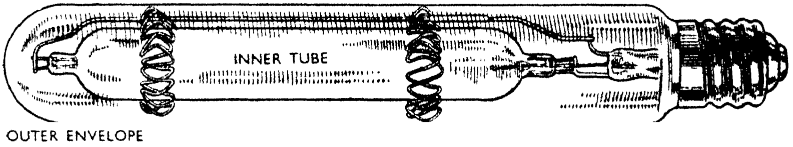
The present-day form of this lamp is represented in Fig. 24, and with the usual electrical connections. The mercury vapour is under pressure in the inner tube of the lamp, and it will be noted that a third electrode is provided in order to start the discharge. This auxiliary electrode is connected through a high resistance to limit the current, and the development of a suitable wire resistance for inclusion in the lamp assembly gave the research workers a problem or two. The normal lamps must be used with the cap upwards.

Deficient in Red Rays

Efficient as this lamp is, it is still not generally acceptable owing to its peculiar light output colour, which is almost entirely deficient in red rays. So experiments continued with a view, not only to correcting the colour, but still further increasing the efficiency.

Before dealing with the later development, however, some mention should be made of the sodium lamp, which is also used for road lighting, and in which a warm yellowish discharge takes place. A typical sodium lamp is shown in Fig. 25, and the discharge takes place in the inner tube. The outer tube acts as a vacuum-flask cover, to maintain the inner tube at an even temperature; when the lamp fails it is necessary only to renew the inner portion. This lamp has found wide application in aerodrome lighting.

With the high-pressure mercury vapour lamp it is found that a great deal of the energy dissipated in the lamp appears as short-wavelength ultra-violet rays, which are normally invisible. Some years



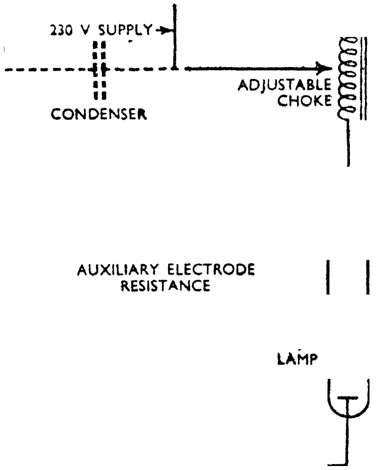
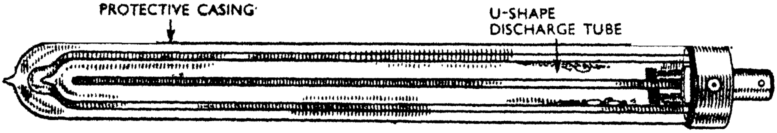


Fig. 24. (Above) Osira high-pressure mercury vapour lamp, consisting of an inner tube containing vapour at high pressure, and an outer envelope protecting the leads to the electrodes. This lamp must be used in conjunction with a line choke, and possibly other accessories. (Left) Connection between main A.C. supply and high-pressure mercury vapour lamp. The auxiliary electrode is used for starting the discharge through the lamp. The condenser may be necessary to correct the low power-factor of the circuit due to the line choke. The latter is necessary, as the lamp itself has no stable resistance.



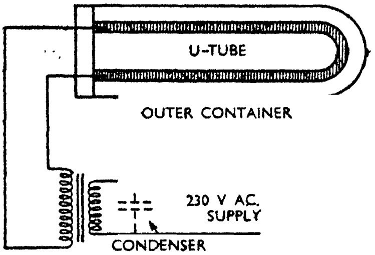


Fig. 25. (Above) Sodium lamp in which the discharge takes place in a U-tube of special construction placed inside an outer tube, necessary to maintain the temperature at the requisite level. (Right) The simple electrical circuit is illustrated. The condenser may be necessary to improve the low power-factor of the line transformer.

ago it was realized that if means could be found to convert these rays into light, an enormous increase in efficiency would be possible. This has now been achieved by spraying special luminescent powders on the inside of the outer bulbs of these lamps.

These powders have the remarkable property of absorbing energy in the form of the hitherto unwanted invisible ultra-violet rays given off by the mercury vapour, and of re-radiating it as visible light of some longer wavelength. The arrangement is drawn in Fig. 26, and in this way suitable powders may be applied, not only to utilize the ultra-violet ray output, but also to improve the colour of the resultant light.

Fluorescent Discharge Lamp

This new lamp is called the fluorescent discharge lamp, and it can be made with a light colour output closely approaching daylight. Although the main application of this lamp at present is for the lighting of factories, offices and workshops, in which a 5-ft. length of tube has an energy consumption of 80 W, workable sizes for domestic use have been developed and cool, shadowless lighting for the home is possible.

In Fig. 27 are shown the accessories required for use with this tubular form of fluorescent lamp, including starting switches. To all intents and purposes the auxiliaries are the same as for the high-pressure mercury vapour lamp, of which this lamp is, of course, a development.

A further development of coating the interior of lamps with fluorescent powders is seen in the lamp with "black glass," which acts as an ultra-violet filter. It is being used for display and other purposes, but especially for laundry uses, in which fluorescent dyes are used for marking fabrics.

These dyes are invisible in ordinary light, so that even the finest fabrics are not disfigured by marking; when the marks are excited by the black-lamp output they become immediately visible.

In talking of the discharge type of lamp and, earlier, of radio-frequency methods of heating, we have been touching on those electrical applications distinguished by the generic title "electronics." This branch of electrical engineering is concerned with those devices,

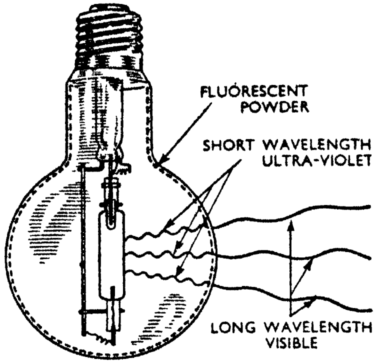


Fig. 26. Principle of the fluorescent [illegible] used for lighting purposes, as it is invisible and, also, cannot penetrate the glass bulb of the lamp. The special coating of the bulb transforms the short-wavelength ultra-violet ray into a longer wavelength visible light.

such as the valve and cathode-ray tube, in which electrons escape from the bounds of solid conductors.

Some people think that electronics will, in a few years, be the most important branch of the electrical industry. This may well be so, since it will embrace radio, television, sound amplification and the innumerable uses of valve apparatus in industry. Already, the industrial applications of valve equipment number about a thousand or more.

Broadcasting

These new electrical services spring up so rapidly that we hardly have time to appreciate their growth. Broadcasting, for example, did not arrive until about 1922 and yet is today providing news and entertainment to millions throughout the entire world. In Britain alone there are over 9,500,000 domestic-type receivers (Fig. 28), representing a considerable capital value, a large "replacement market" for new sets and parts such as valves, and calling for the services of thousands of producers, salesmen and repairmen.

Television

Throughout the world there are thousands of transmitters with all their complex apparatus, from microphones to towering aerials (Fig. 29). As television becomes universal there will be an appreciable increase in the elaboration of both transmitters and

We shall all become familiar with cathode-ray tubes of a perfection and size which, a score of years back, would have roused the envy and despair of the wealthiest scientist. Television "pick-up" units will be at every important

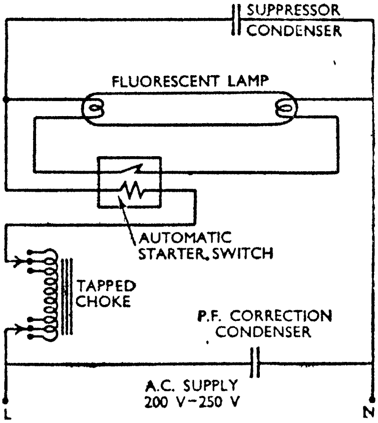


Fig. 27. Connections of a 5-ft. fluorescent lamp, in which form this lamp is generally used. The discharge is started by the heating of the electrodes, and as soon as these have reached the operating temperature, the heating current is cut off by means of the starter switch. Two condensers are used, one for power-factor correction and the other to suppress interference with radio reception.

function, side by side with the film cameras.

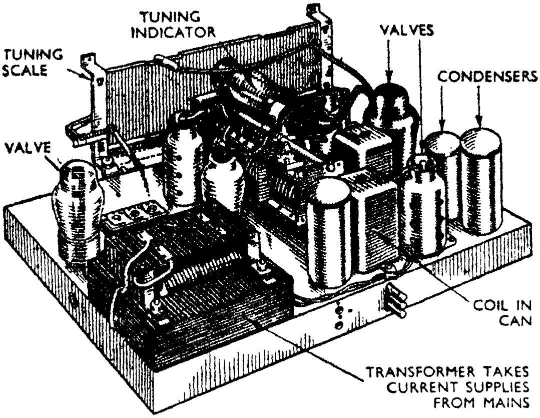


Fig. 28. Although they are complex scientific instruments, radio sets are mass produced at low prices for domestic use. In Britain there are over 9,500,000.

The television programmes (Fig. 30), on ultra-short wavelengths, will be relayed from the studios to the transmitters over a nationwide network of very-high-frequency "beams." These short wavelengths also open up the possibility of scores of new transmitters giving sound programmes over limited "local" areas. A frequency-modulation system will give much more realistic reproduction, with less background noise and interference.

"Radio" programmes will also be widely distributed by wire, special "relay" wires or the ordinary telephone or mains wires. Some of these circuits will employ radio-frequency "carrier" currents and will entail the use of both transmitters and receivers.

Carrier-current technique has, in fact, been in use for telephone and telegraph circuits for several years.

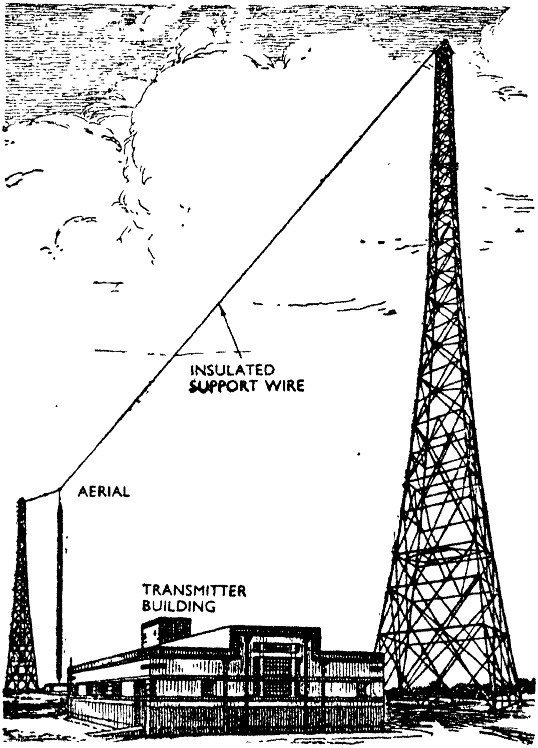


Fig. 29. Marconi broadcasting station. These powerful transmitting stations are scattered all over the world.

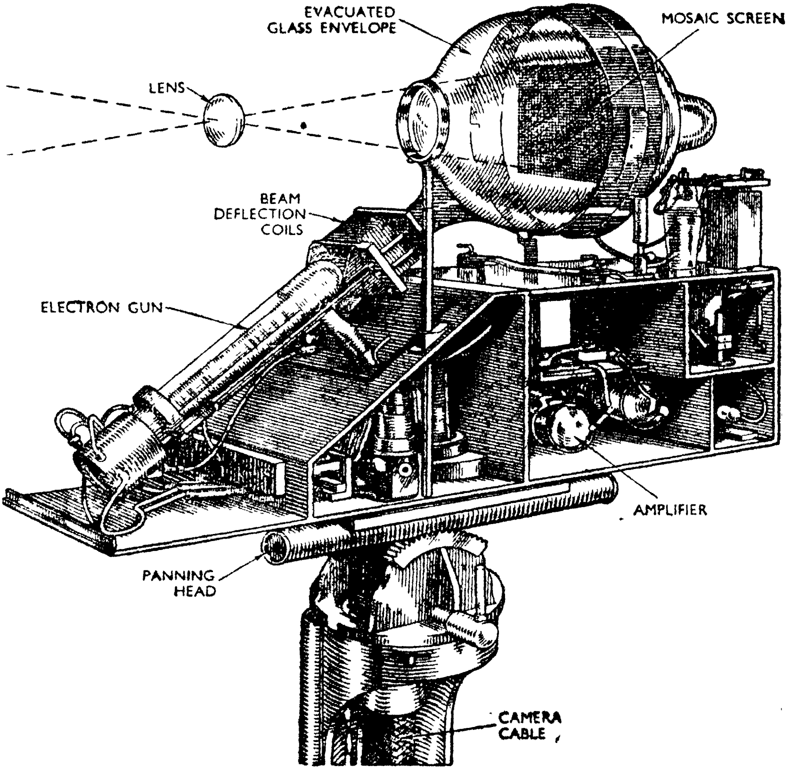
Just as numerous radio-frequency carrier waves can travel through the same ether, so can dozens of carrier currents be passed over a single cable and then sorted out, by "tuning" circuits, at the far end of the line.

Valve Amplifiers

Nowadays, the ordinary telephone and cable circuits make great use of valve amplifiers, which are inserted at regular intervals to compensate for the inevitable losses. Water-tight amplifiers, entirely automatic and good for years of operation, are connected to submarine cables.

These commercial forms of communication remind us of the parallel uses of radio. Broadcasting to the public is only a section of radio. There are the great communication organizations whose business it is to transmit business cables, phone calls, and news round the world. These mainly employ the short-wave "beam" systems.

Then there are radio applications



WORKING DETAILS OF A TELEVISION CAMERA

Fig. 30. This illustration indicates in detail the type of "camera" used in a television transmission. Light reflected from scene being televised is focused on to mosaic screen by a lens. Mosaic screen consists of a mass of tiny photo-electric cells.

to mobile services: aeroplanes, ships, police and fire cars, trains and so on. For example, a plane will probably employ radio for all the following purposes: talking to airport controllers, passenger telephone calls or cables, position finding, "blind" landing, height finding and collision prevention. Direction-giving stations and radio beacons (or "lighthouses") are two of the corresponding ground services.

Ships employ radio on the grand scale for communication, navigation and safety; they even plot a chart of the sea-bed by radio technique. Railways are a comparatively recent convert to radio, but little hand-type radio telephone sets are now being used for talking between drivers and guards, signalmen and shunters. Flying-boats and harbour launches also find these units invaluable.

Radio on Cars

"Calling all cars" is another radio contribution to safety; and the time is not too far off, perhaps, when the ordinary motorist, in addition to broadcast listening as he drives, will be able to radio to his home or office.

The use of the valve for amplification solely of sound-frequency currents has built a large off-shoot of the radio industry and has contributed vitally to other industries. Sound amplification, or "public address" (Fig. 31), has hundreds of uses, from "putting over" the after-dinner speech to the information of vast outdoor crowds. Railways, shops, offices, hotels, restaurants, churches, fairgrounds, dance-halls and ships are some of the places where PA is now indispensable, and who needs reminding of music-while-you-work in factories?

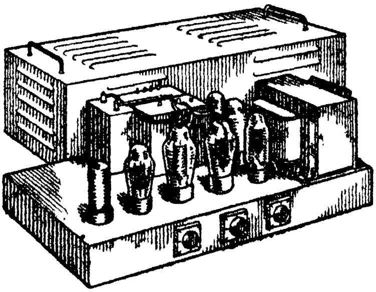


Fig. 31. Power amplifier forming part of a public-address system of sound amplification.

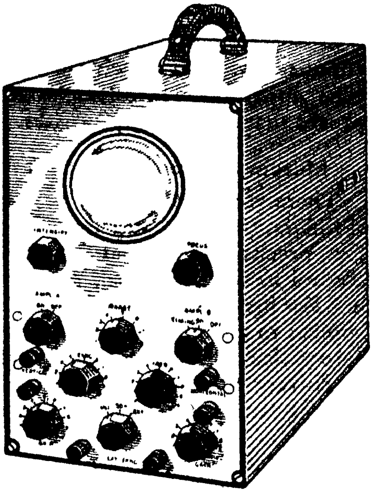


Fig. 32. Cathode-ray tube is embodied in this oscillograph, permitting the user to see what happens in an electrical circuit at any particular moment.

Talking Film

The talking film is possible because of the valve, and the modern theatre makes extensive use of amplification and of recorded effects. The recording of sound, on wax, film, wire or tape, is yet another application which has created a fair-sized industry. Now, turning to what are called "industrial electronics," we come to countless ways in which vacuum-tube apparatus controls and improves manufacturing processes.

Mercury Vapour Rectifiers

There are great mercury vapour rectifiers, ignitrons and thyratrons for precise relay and current-control in such processes as welding. For instance, electronic control applied to a welding machine may automatically attend to the length of current flow, the temperature, the mechanical pressure, the frequency of current pulses and the duration of the intervals.

Valve circuits, "triggered" off by some minute impulse, can operate various controls by means of relays and do so in a timed sequence.

Derived from the valve, the cathode-ray tube has grown into what is probably the most remarkable and adaptable of electrical instruments. Embodied in an oscillograph (Fig. 32), it enables us actually to see what happens in an electrical circuit, even if the happening occupies only a minute fraction of a second. With suitable pick-up devices, which change movement, temperature or pressure into current, it has applications in every research laboratory and in most engineering workshops.

The cathode-ray tube makes television possible, and it also gives us an entirely new method of testing radio and television sets and many types of electrical apparatus.

Light-sensitive Cell

Another branch of electronics springs from the light-sensitive cell. The oldest form is known as the selenium bridge, which comprises an assembly of electrodes between which the conducting path is selenium. These are virtually resistances whose resistance falls or increases as the light falling upon them is greater or less. The "dark" resistance ranges from 0·5 to 20 megohms, according to purpose for which bridge is required.

The selenium self-generating cell contains a ferrous metal plate coated with selenium on one side, over which a very thin conductor of metal is deposited. The actual light-sensitive action is not yet fully understood, but the electrodes, when dark, are at equipotential, and no current flows in the external circuit. When the cell is illuminated and the external circuit is of low resistance, the cell develops a potential and current which is linear with respect to light intensity.

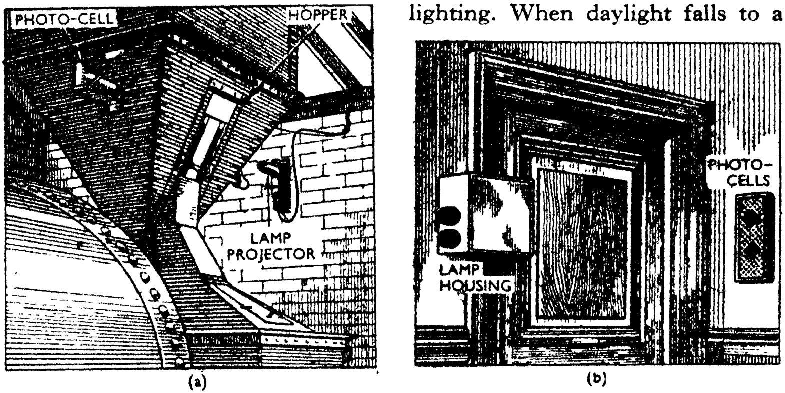
Commercial Use

Currents amounting to several milliamperes may be developed in quite small cells; but as the e.m.f. never exceeds a fraction of a volt, the currents do not readily lend themselves to valve amplification, and a device known as a light-sensitive cell is more often used for commercial applications.

These are also known as photo-electric, or more commonly, photo-cells, and the fundamental construction of these comprises two electrodes in a tube, which may be gas-filled or vacuum; the former is the more common. The cathode, or light-sensitive element, is a metallic conductor coated with a layer of suitable alkali, and an anode is used to collect the electrons emitted from the cathode.

The anode can be of any metal, almost, and any shape or form. The cathode and actuating material are varied, each type having its own electron-emitting and light-response characteristics. In full darkness, the electron emission from the cathode is nil, and the resistance of the cell is infinite. In light, with the application of a potential to the anode, electron emission is created and current flows.

Even with very bright light, the current passing is very small, amounting to a few micro-amperes only, and great care is necessary in the circuit arrangements to prevent this small output being lost by leakage. The gas-filled photo-cell gives a. greater output than the vacuum cell; the currents are still very small, but they are capable of amplification by means of suitable valve circuits.



(a) (b)

"ELECTRIC EYE" IN ACTION

Fig. 33. Two practical applications of the photo-electric cell. (a) Shows how it can be applied to a coal bunker so that by means of a light ray passing through a hopper, the contents can be kept automatically at a suitable level. (b) Invisible infra-red ray and photo-cell used in a burglar-alarm system in a bank building.

The applications of photo-cells are almost without number, and include such things as the opening and closing of doors, the counting of traffic passing a given point, television "pick-up," and the scanning for reproduction of the sound-track of cinematograph films. The sending of photographs by wire or radio, and the transmitting of facsimile documents are also due to the development of the light-sensitive cell.

"Electric Eye"

Typical industrial applications are pictured in Figs. 33 and 34, and the "electric eye" is now charged with the duty of guarding national treasures and the control of artificial lighting. When daylight falls to a low ebb, due to fog or the approach of darkness, the photo-cell will operate a relay, switching on one or more lights as required. In fact, its uses and possibilities are, like its heated-cathode counterpart, without limit.

A simple circuit, the basis of most commercial applications, employing a photo-cell and standard amplifying valve, is reproduced in Fig. 35.

To round off this chapter we cannot do better than take a glance at some of the ways electricity assists man to fight disease and maintain health. The applications of electricity to medicine and surgery are, indeed, now so wide and important that only the briefest reference can be made to them.

X-rays

The X-ray has been developed to the point where tissue structures may be examined in addition to bones and foreign objects lodged in the body. The spread of tuberculosis has been checked by systematic examination of the lungs of hundreds of thousands of workers in factories and offices.

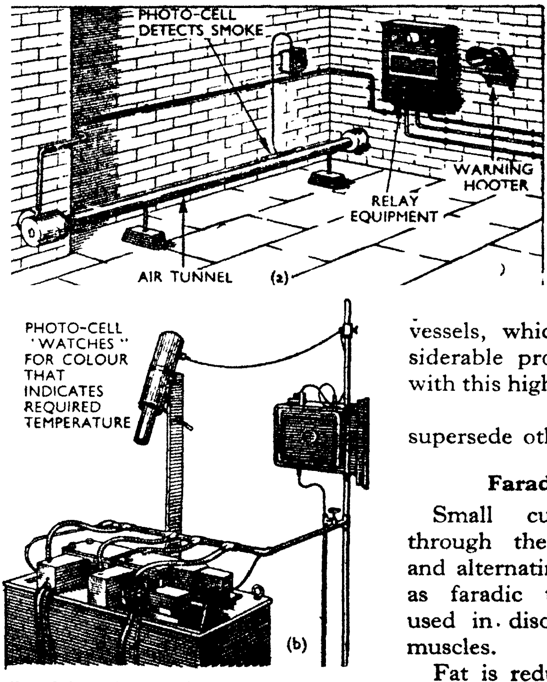


Fig. 34. (a) Fire-detection apparatus installed in a generating station. Air is drawn from the cable ducts into the long tube, and if the photo-cell detects the presence of smoke it will operate the warning hooter. (b) Light cell may "watch" for a particular radiation and thus give an indication when a metal bar reaches a certain temperature.

Powerful X-ray generators are now used for the treatment of deep-seated growths and tumours, not amenable to other forms of treatment. High-frequency currents are employed in what is known as diathermy, or "heating-through," on the principle of the application already described. With this, heat is induced in deep tissues without risk of burning the skin, and good results are reported.

Another interesting use of high-frequency currents is in connection with surgery, where the spark from the special tool is used for the actual severing or cutting of flesh. In addition to performing this operation with speed, the action of the current tends to cauterize the wound and at the same time prevents excessive bleeding from the smaller vessels, which it seals off. Considerable progress is being made with this high-frequency knife, and

supersede other methods.

Faradic Treatment

Small currents are passed through the body, both direct and alternating, in what is known as faradic treatment, which is used in disorders of nerves and muscles.

Fat is reduced in the Bergonie

trolled exercises, which cause no effort or fatigue to the patient. The muscles are moved by means of carefully timed and regulated electric currents whilst the patient is seated comfortably in a chair.

Local anæsthesia can be produced by means of electric currents, but this method has not yet enjoyed wide popularity in this country. Electric lighting is the only method whereby internal organs may be illuminated for examination by the surgeon. These electrical applications are by no means confined to human beings, as the veterinary surgeon finds them of value in dealing with animals.

Ultra-violet Rays

One of the most widespread applications of electricity to health measures is undoubtedly that of irradiation, or the application of ultra-violet rays. Not only are these rays applied to the human body, but they are used in the sterilization of liquids, such as milk, and in the preparation of foods of all kinds. This ensures complete freedom from germs, and undrinkable water exposed for a few minutes to ultra-violet rays becomes suitable for human consumption.

In the radiant lamps used in the home (Fig. 36) the intensity of the ray is greater than that found in nature, and even a small ultra-violet lamp may cause serious sunburns if used carelessly. An hour with a sun-lamp may be the equivalent of a day in strong sunshine at the seaside, and the painful effects of sunburn are quite well known without stressing it here.

Sun-lamps

With care, a sun-lamp in the home is a valuable form of tonic, and may be used with benefit for the youngest members of the family and the most sensitive skins. It is usual to protect the eyes from harmful effect of the rays by the wearing of dark glasses designed to obstruct the ultra-violet ray, and treatment should never be undertaken without them.

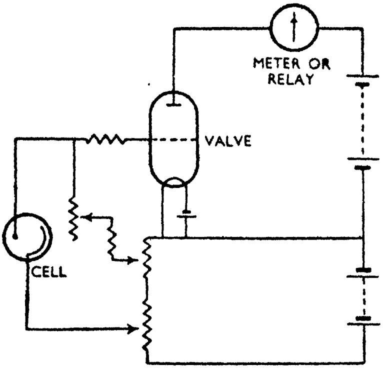


Fig. 35. Simple circuit comprising a photo-electric cell, on left, connected through an amplifying valve to a relay. When current passes from the light-sensitive screen to the anode of the photo-electric cell, a small positive charge is applied to the grid of the amplifying valve. This causes current to pass through this valve, from the battery shown on the right, and the relay is operated. When light ceases to operate the cell, the grid charge is then dissipated by the resistance connected, and current through the amplifying valve is interrupted, opening the relay.

Another form of health lamp is the infra-red generator. This, in effect, produces radiations at the heat end of the spectrum; these radiations are felt as warmth and penetrate the body deeper than ultra-violet rays. They work beneficially by stimulating blood circulation.

There is no end to the services electricity renders to mankind, just as there is no end to its development.

Electricity, as the study of the electron reveals, is a part of the fabric of the universe itself and the more we learn about it the deeper our understanding of the great natural mysteries. At the same time, electricity gives us new theories and new instruments of revolutionary importance in all other fields of science from chemistry to biology and even psychology.

To a great extent, the future well-being of the work is in the hands of the electrical engineer; that he will not fail can be assumed from his past record.

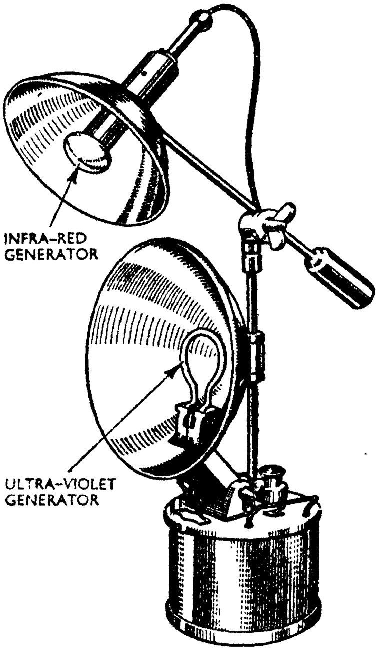


Fig. 36. Designed for treatment in the clinic, surgery or at home, this twin-ray ultra-violet and high-power infra-red apparatus is an interesting example of electro-medical engineering. It is fitted with two quick make-and-break switches so that the rays can be used together or separately. A comparatively short period of time with a "sun-lamp" is considered equivalent to a day in the sun at the seaside. Many factories are now equipped with such apparatus for the benefit of their employees. Treatment should never be taken from these electro-medical devices except under the direct supervision of a fully qualified expert.

It is, perhaps, proper to end this book with a few words to the younger readers on whom the future of the electrical industry depends. The industry is one of the greatest consequence, not only because of its direct contribution to the standard of living of the people of Britain, but also because it is one on which the country relies for a great, and growing, part of its export trade. So, in the hands of our young engineers there lies a very large part of the ability of this country to earn its vital imports of raw materials and food.

In the past, this country has been a big exporter of many manufactured goods, but overseas countries are themselves becoming industrialized and able to make many of the goods they formerly imported from us. It follows that in the years ahead our exports must largely be of those articles which demand a higher level of technical skill, in both the design and production stages, than is available in most of the newer industrial countries.

With her large population centred in relatively few areas, and with a long tradition of learning and skill, Britain is in a favourable position as a maker of specialized and advanced equipments. It is also evident that a large proportion of these equipments will be of an electrical and radio character.

Part of the native genius seems to lie in such work: it can hardly be by chance that most of the great electrical and radio discoveries —from Faraday's fundamental experiments to the war-saving inventions of radiolocation—have been made in the British Isles.

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